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SOME CHARACTERISTICS OF THE EPPLEY PYRHELIOMETER

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ABSTRACT

Tests were made of the effect of several variables on the performance of the Eppley pyrheliometer. The tests showed: (1) How the output increased with decreasing ambient temperature; (2) how output varied with angle of incidence of collimated radiation; (3) that output decreased about 5 percent when receiver was exposed in the vertical plane, but that complete inversion from the horizontal had no significant effect; and (4) that a few water droplets on the glass envelope did not influence output. In addition, spectral transmission data, from National Bureau of Standards tests, are shown.

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INTRODUCTION

Recent measurements of solar radiation by means of Eppley pyrheliometers mounted on aircraft [1] have made it desirable to determine the response of that instrument under some of the conditions of exposure in flight and the variation in response characteristic of pyrheliometers exposed under similar conditions. Tests giving some of these data (on effects of temperature, and "cosine response" primarily) have been completed at the Instrument Division of the Weather Bureau, and it is the purpose of this paper to report the results and compare them with other available similar data. Also included are data on spectral characteristics, obtained by the National Bureau of Standards for the Weather Bureau.

THE EPPLEY PYRHELIOMETER

The Eppley pyrheliometer (fig. 1) consists of a thermopile mounted under receivers inside a clear glass spherical bulb about 3 inches in diameter. The thermocouples are platinum-rhodium (90−10 percent) and gold-palladium (60–40 percent) [2] and the thermopile comprises either ten or fifty thermocouples [2] depending on the output the particular instrument was designed to produce. The receivers are concentric flat metal rings exposed in a common plane; the rings are thermally insulated from each other and from the mounting. One ring is coated with magnesium oxide; to the underside of this the electrically insulated cold junctions are attached in close thermal contact. The other ring is coated with lampblack; the hot junctions are similarly attached to its undersurface. The magnesium oxide has a high reflectivity for radiation in the solar wave lengths and is a good absorber and emitter in the longer wave lengths (e. g. [3], p. 2241), making for a low equilibrium temperature on exposure to solar radiation. Lampblack has good absorption

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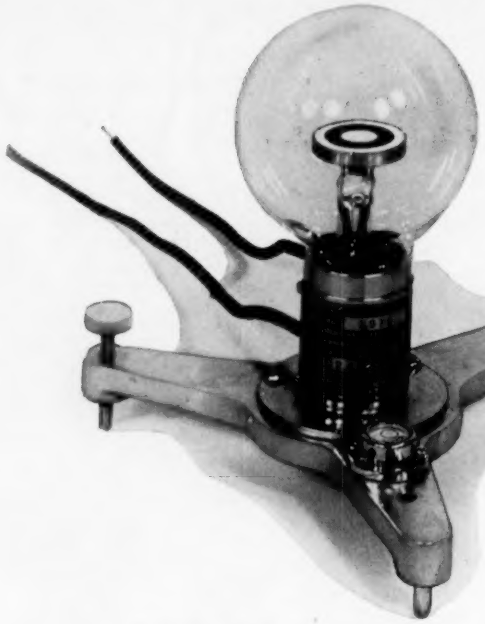

FIGURE 1.—The Eppley pyrheliometer.

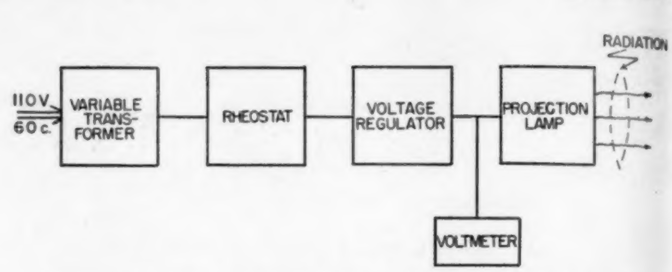

FIGURE 2.—Block diagram of radiation-generating equipment used in tests.

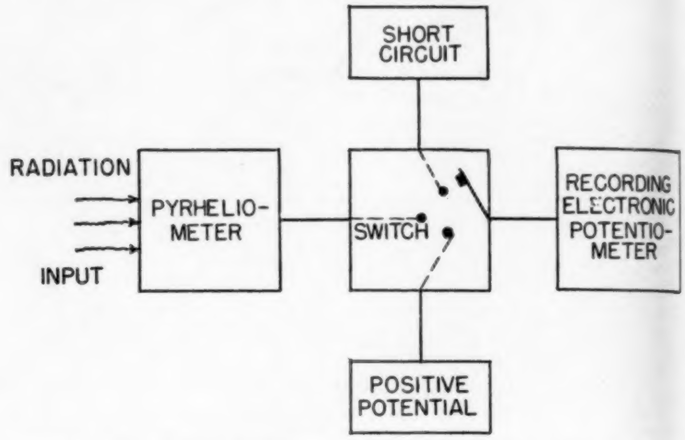

FIGURE 3.—Block diagram of pyrheliometer and output-measuring circuit used in tests.

characteristics in both wave length intervals, and due to its greater absorption of the solar wave lengths its equilibrium temperature on exposure to solar radiation is higher than that of the magnesium oxide. The similarity of the receivers with regard to absorption of long wave radiation tends to minimize the effect of any long wave radiation (as from the glass cover) which may fall on the receivers. The bulb contains dry air [2]. The over-all response of the instrument to solar radiation is an e. m. f. rather closely proportional to solar radiation flux density through the plane of the receivers.

EQUIPMENT USED IN TESTS

The equipment for examining the effects of temperature and angle of incidence ("cosine response") on the response of the Eppley pyrheliometer consisted of (*a*) a radiation-generating unit, (*b*) mounting for the pyrheliometer on either a moveable disc or inside a "temperature box," and (*c*) a recording potentiometer. Figure 2 is a block diagram of the radiation generating part of the equipment. Voltage from the 110-volt, 60-cycle, 1-phase line was brought to approximately 100 volts in the variable transformer and more exactly to that value in the rheostat, and was stabilized by a voltage regulator. It was necessary to monitor the voltage across the lamp with a voltmeter to guard against any persistent small variations in the line voltage. A mazda projection lamp whose radiation output was quite stable, as indicated by periodic checks by the National Bureau of Standards, was the source of radiation. Figure 3 is a block diagram showing the pyrheliometer (which was mounted on a movable disc or in the temperature box or on a rotating channel iron) and output-measuring circuit. The output leads from the pyrheliometer were brought to the recording potentiometer through a switching arrangement for convenience in making zero reference marks and time checks on the record. The recorder input leads could be short-circuited to move the pen downscale, or switched to a source of positive potential for an up-scale reference mark.

TEMPERATURE TESTS

TEMPERATURE BOX

The temperature box (fig. 4) used in making temperature tests was made up of two sections. One section for dry ice was situated above the other section, the radiation chamber, in which the pyrheliometer was mounted. The two sections were connected by adjustable louvres. For the low temperature values, air was forced by a fan over the dry ice down through one louvre into the radiation chamber, and returned to the dry-ice compartment upward through the second louvre. There was enough turbulence to keep the air well mixed. For high temperatures the louvres were closed and electric current was metered by means of a variable transformer into heating coils located in the radiation chamber. By these means, temperature could be kept at any level between −40° F. and +120° F., to within 2° or 3°. Radiation from the lamp was admitted through a glass window in the side of the radiation chamber to fall on the vertically-mounted pyrheliometer. The flux density was about a half langley per minute, as shown by the pyrheliometers.

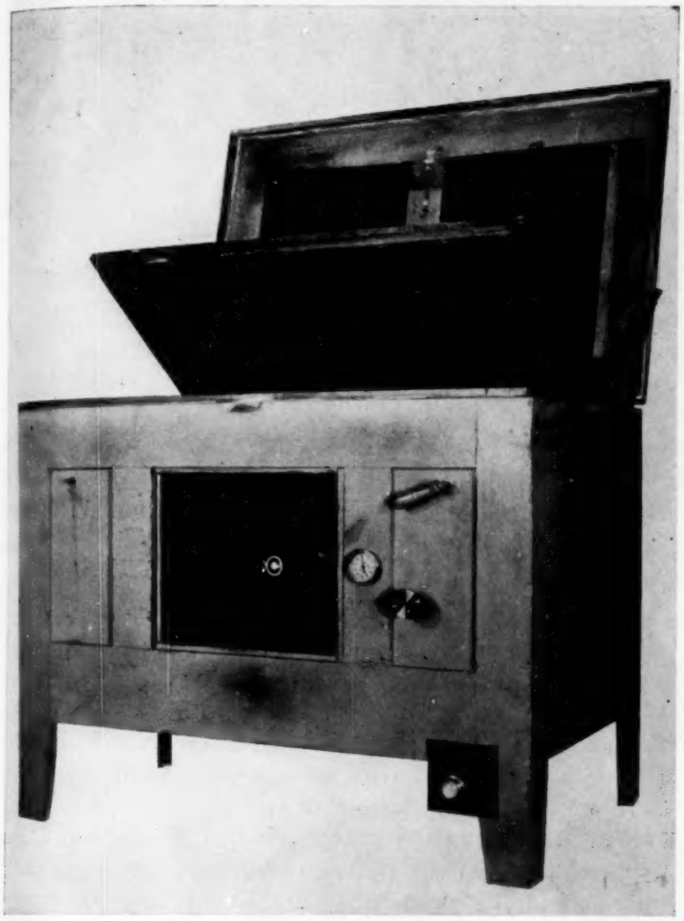

FIGURE 4.—Temperature box used in tests.

Beginning at 80° F., temperatures were varied by 40° increments and kept at each test point for about 25 minutes. It was necessary to hold the temperatures constant over this rather large time interval to avoid the effects of a substantial "overshoot" of pyrheliometer response. For colder temperatures the equilibrium response is higher than for warmer temperatures Nevertheless, with rapid lowering of temperature from one test point to another, the response would increase by a few percent *above* its equilibrium value for the colder test point. The response then gradually diminished to equilibrium during a period of 20 minutes or so depending on the preceding time-rate-of-change of temperature. An increase in temperature resulted in a corresponding *undershooting* of equilibrium response. It will be recognized that this effect differs from an ordinary "lag" effect. (The instrument would not be affected in this way by rates of change of temperature associated with weather.)

RESULTS OF TEMPERATURE TESTS

Figure 5 shows data obtained for five pyrheliometers, plus data obtained previously for two others by the National Bureau of Standards [6]. (The original Bureau of Standards data were given in more detail, being given at increments of 10° C.) The data are also given in

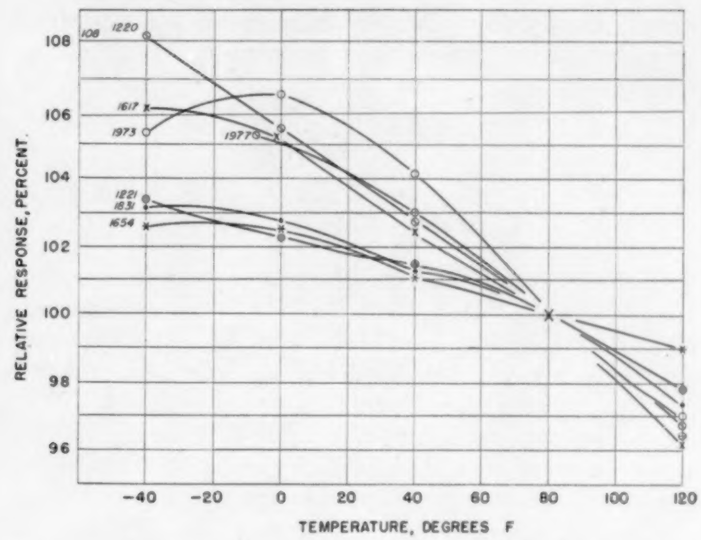

FIGURE 5.—Relative response as a function of temperature, for five pyrheliometers (Nos. 1617, 1654, 1831, 1973, and 1977) tested by Weather Bureau and two others (Nos. 1220 and 1221) tested by National Bureau of Standards [6].

TABLE 1.—*Effect of ambient temperature on response of Eppley Pyrheliometers. Tabulations of response are given in percent of response at 80° F.*

Temperature		Pyrheliometers No.—							Average (of the 7)
		1617	1654	1831	1973	1977	1220	1221	
° C.	° F.	Weather Bureau tests					Bureau of Standards tests		
−40	−40	106.2	102.7	103.1	105.4	----	108.1	103.3	104.8
−17.8	0	105.2	102.5	102.7	106.5	105.1	105.5	102.4	104.3
+4.4	+40	102.4	101.1	101.1	104.1	103.0	102.8	101.4	102.3
+26.7	+80	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
+48.9	+120	96.2	99.0	97.3	97.0	96.4	96.7	97.8	97.2

table 1. The responses are in terms of response at 80° F. which is arbitrarily assigned the value of 100 percent.

CAUSES OF TEMPERATURE EFFECTS

It will be noted that the response decreases with higher temperatures. This appears to be due to a decrease in the difference in temperature between the black and white receivers rather than a diminution of the "efficiency" of the thermocouples comprising the thermopile. By efficiency is meant the output per degree of temperature difference between hot and cold junctions. This can be seen from the performance equation of one thermocouple of the kind comprising the pile [4]:

$$E=32.975\ T+.03881\ T^2 \tag{1}$$

where T is the temperature of the hot junction in degrees Centigrade, the cold junction being at zero; E is e. m. f. in microvolts (μV). This implies (e. g., Loeb [5]) the relationship

$$E=32.975\ (T_h-T_c)+.03881\ (T_h^2-T_c^2) \tag{2}$$

where the subscripts h and c indicate hot and cold junc-

tions, respectively. If the difference of temperature between the two junctions is assumed to remain a constant, k,

$$E=32.975k+.03881k(2T_h-k) \tag{3}$$

$$dE=\frac{\partial E}{\partial T_h}\,dT_h=.07762k\,dT_h. \tag{4}$$

This shows that an increase of .0776 μV in e. m. f. output should occur for each 1° C. increase in the temperature of the hot junction (provided a one degree temperature difference between the hot and cold junctions is maintained), for each thermocouple in the thermopile. Since (with constant radiation) the output of the pyrheliometer *diminishes* with increasing ambient temperature instead of increasing as equation (4) suggests should be the case, it appears that the temperature difference between the hot and cold junctions diminishes with increasing ambient temperature. This may be due to convection inside the glass bulb. Convection effects may also explain the diminishing output of the pyrheliometer when exposed in the vertical plane as will be described later.

COSINE RESPONSE TESTS

PYRHELIOMETER MOUNTING

For the cosine response tests, i. e., tests of the effect of the angle of incidence on response, the pyrheliometer was mounted on a pair of plates taken from an old surveying level. The fixed plate was marked in degrees and fractions and the rotating plate, to which the pyrheliometer was rigidly fixed, contained a vernier for accurate reading of the angular displacement from the zero reference mark of the fixed plate. Unwanted reflections from extraneous sources were suppressed by draping the reflecting surfaces with black cloth. Figure 6 shows the equipment with some of the radiation-shielding cloth removed (recording equipment is not shown). The pyrheliometer was mounted vertically so the axis of rotation of the plate was in the plane of the black and white annular receivers—that is, the axis of rotation coincided with the vertical diameter of the receiver. The center of the receiver was also in the center of the horizontally-directed radiation beam. Levels and a cathetometer, shown in figure 6, were used in this alignment. Rotation of the plate changed the angle of incidence of the radiation on the receiver by an amount indicated by the vernier. Since the area of the beam (as measured in a plane normal to its direction of propagation) intercepted by the receiver was proportional to the cosine of the angle of incidence, the e. m. f. should have been proportional to the cosine of the angle of incidence if the instrument had been perfect (perfect, that is, in that for a given flux density across the plane of the receiver the response should be independent of the angle of incidence; and for any fixed angle of incidence the response should be linear with radiation flux density).

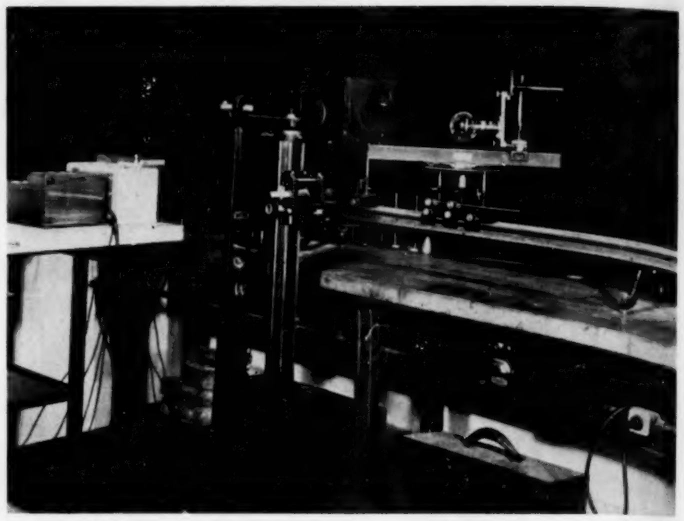

FIGURE 6.—Mounting of pyrheliometer and other equipment used in cosine response tests. Recording equipment is not shown.

RESULTS OF COSINE RESPONSE TESTS

Two pyrheliometers were tested. Figure 7 shows the results obtained from the present tests (for pyrheliometers 1754 and 1973) and data obtained in similar tests by the Bureau of Standards [6] (for pyrheliometers 1220 and 1221). The data are also given in table 2 (Bureau of Standards data were for 10° increments of angle of incidence; part of data is omitted in this table). Woertz and Hand [7] made tests using different techniques, but analysis of their data indicates similarity to the other response curves (except No. 1754).

For perfect calibration, all of the points in figure 7 should have coincided with the solid line. It is difficult to judge from this the percent of error associated with the points. To illustrate the percent of the true response actually given by the pyrheliometers, the ratio of the ordinates of the points in figure 7 to the corresponding ordinates of the true cosine curve were computed and the results are shown in figure 8. The various pyrheliometers show fair agreement except for No. 1754. That instru-

TABLE 2.—*Effect of angle of incidence on response of Eppley pyrheliometers. Tabulations are the percent of the correct response shown by the instruments at different angles of incidence α. Response is arbitrarily assumed 100 percent at $\alpha=0$.*

Angle of incidence α	Pyrheliometers No. —			
	1754	1973	1220	1221
	(Weather Bureau tests [1])		(Bureau of Standards tests [2])	
0	100	100	100	100
30	103	100	102	102
60	105	101	100	99
70	-------	-----	94	96
75	101	-----	-----	-----
80	-------	79	81	82
85	103	-----	-----	-----
90	$+\infty$ in 3 of 4 paths	$+\infty$	$-\infty$	$-\infty$

[1] Results given are averages of 4 paths.
[2] Results given are averages of 2 paths.

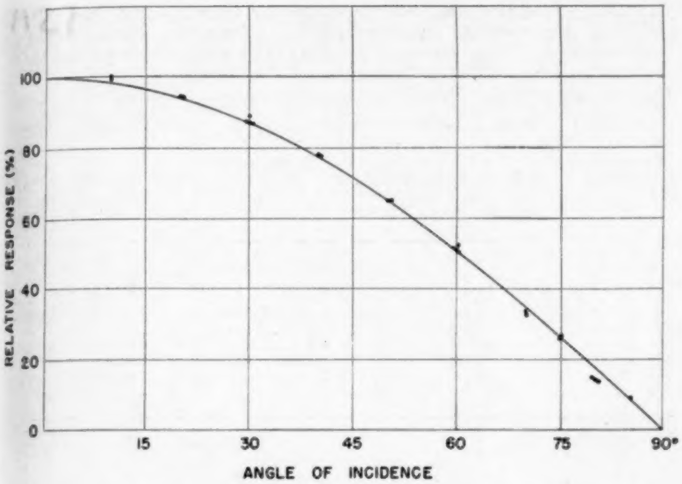

FIGURE 7.—Relative response as a function of angle of incidence of collumated radiation, for two pyrheliometers (Nos. 1754 and 1973) tested by Weather Bureau and two others (Nos. 1220 and 1221) tested by National Bureau of Standards [6]. Response assumed correct at zero angle of incidence. Curve is theoretically perfect response, i. e., cosine of angle of incidence.

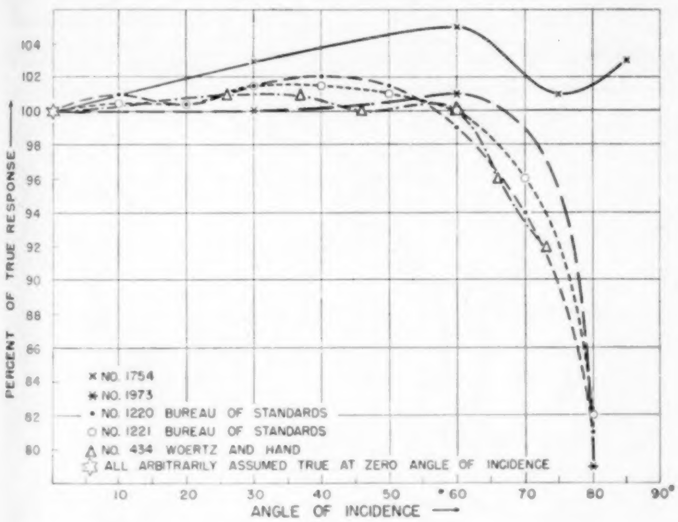

FIGURE 8.—Percent of true response as a function of angle of incidence computed for data given in figure 7 and for data from a test by Woertz and Hand [7].

ment showed a higher response near 80° angle of incidence than the others. (Woertz and Hand data went only to 78°. The response at $\alpha=\cos^{-1} 0.9$, about 25°, was arbitrarily assumed to be 101 percent since normal incidence response was not indicated.)

CAUSES OF COSINE EFFECTS

The deviations from "true calibration" with angle of incidence could be due to either or both of two classes of effects: (*a*) Nonlinearity of e. m. f. with radiation flux density, or (*b*) dependence of response on angle of incidence, assuming constant flux density through the plane of the receivers. It seems to have been generally assumed that (*a*) is unimportant as compared to (*b*), and in previous cosine tests (*a*) was not mentioned as a possible factor in the observed cosine response. Several causes

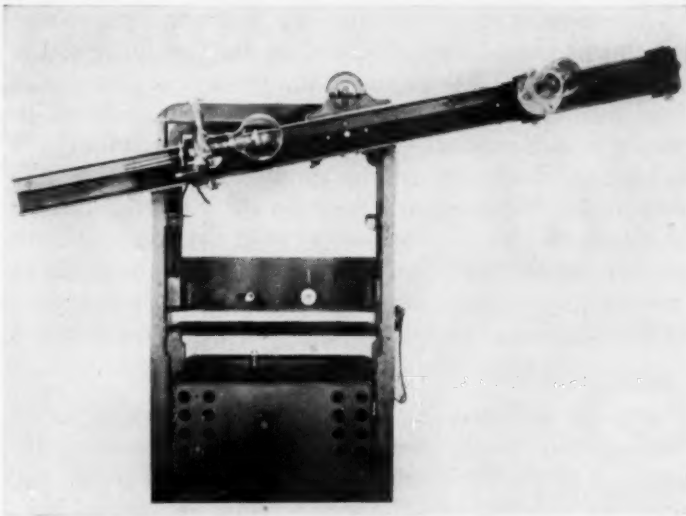

FIGURE 9.—Mounting of pyrheliometer for testing effect of variations in inclination of plane of the receiver. The pyrheliometer is at the left, the radiation lamp at the right.

have been suggested for (*b*), among them the possible dependency on angle of incidence of the absorption of the lampblack (Miller, [8], [9]). Woertz and Hand [7] suggested among other possibilities that the black and white receivers might not be in exactly the same plane, and that irregularity in the glass envelope might be a factor. It might be noted that if (*a*) is of the same general order of magnitude as (or greater than) (*b*), the cosine response curve will be affected significantly by flux density (as measured on a surface normal to the direction of propagation of the radiation beam). This remains to be determined.

MISCELLANEOUS TESTS

EFFECT OF MOUNTING PYRHELIOMETER VERTICALLY

In order to test for variations in pyrheliometer output with inclination of the plane of the receiver, the pyrheliometer and lamp were rigidly mounted about 2 feet apart on a section of channel iron. The arrangement was such that radiation from the lamp was incident on the pyrheliometer at an angle of incidence (approximately "normal incidence") which was unchanged as the iron was rotated through a vertical plane about a pivot in the center of the long axis of the channel iron. (See fig. 9.) The pyrheliometer was protected from random reflections by a shield constructed from an old camera bellows. It was necessary to force-ventilate the pyrheliometer by means of an independently mounted blower to avoid temperature rises. As a control, a photo-voltaic cell was mounted in a similar way, and showed no variation in output when the rail was rotated in steps.

Tests were made with two pyrheliometers. The results showed no significant change in output for the inverted position as compared with the horizontal position, but indicated a decrease of 4 or 5 percent in output when the pyrheliometer receiver was in the vertical plane. This may have been due to convection current effects within the pyrheliometer glass envelope.

These results suggested that the temperature response data might have been influenced by the mounting of the pyrheliometer with the receiver in the vertical plane. To check this, an arrangement was made whereby the pyrheliometer was mounted with the receiver horizontal and facing up. Radiation coming through the window of the temperature box was then reflected to the pyrheliometer by a mirror. The temperature curve obtained with the original vertical mounting was repeated without significant variation; apparently the temperature effect is the same for horizontal and vertical positions of the pyrheliometer.

EFFECT OF WATER DROPS ON THE PYRHELIOMETER

In order to determine whether raindrops would affect the radiation measurements by the pyrheliometer significantly, a pyrheliometer was exposed on the roof, and sprinkled with water from a sponge. While it would have been easy to detect a change in output of well under 1 percent, no change was detected. Evidently the effect of a few raindrops on solar radiation measurements with the pyrheliometer is negligible.

SPECTRAL TRANSMISSION OF GLASS ENVELOPE

The National Bureau of Standards has made for the Weather Bureau tests of the transmission of two samples of the glass from which the pyrheliometer covers are made. The following is from the Bureau of Standards letter of transmittal:

"* * * With reference to the conference on Tuesday, March 27, 1951, between Messrs. Norman B. Foster and Torrence MacDonald of the U. S. Weather Bureau and members of the Radiometry Laboratory of this Bureau, transmission measurements have been made on samples of glass taken from two Eppley pyrheliometer glass envelopes previously submitted to this laboratory by the Eppley Laboratory. For these tests sections of about 1 by 1 inch were taken from the upper one-half of the bulb hemisphere (centered about midway between the zenith and horizontal positions). In the case of each bulb the thickness ranged from about 1.0 mm. at the zenith to about 0.5 mm. at the horizontal position. Hence, the samples examined were wedge shaped. This fact coupled with the curvature of the specimens rendered precise transmission measurements difficult. Transmission measurements through the ultraviolet, visible, and to 1100 millimicrons in the infrared as obtained with a Bechman quartz spectrophotometer are given in the accompanying table. Spectrograms as obtained with a Perkin-Elmer double-beam infrared recording spectrophotometer are enclosed for the infrared spectral region. Because of the peculiar focusing effects resulting from the curvature and wedge shape of the samples the transmission data are subject to small indefinite errors. In particular in the case of the infrared curve for sample No. 1, the ordinates should probably be multiplied by about 1.02. An additional correction is required in the case of the infrared curves because of the slight drift of the 100-percent instrument response as a function of wave length. The ordinates for the sample curve are simply to be divided by value recorded on the 100-percent curve."

TABLE 3.—*Transmission measurements for wave lengths from 0.280 to 1.100 microns made on samples of glass from two Eppley pyrheliometer bulbs. Measurements obtained with a Bechman quartz spectrophotometer by National Bureau of Standards*

Wave length (microns)	Transmittance (percent)		Wave length (microns)	Transmittance (percent)	
	Bulb No. 1 (thickness =0.78 mm.)	Bulb No. 2 (thickness =0.79 mm.)		Bulb No. 1 (thickness =.078 mm.)	Bulb No. 2 (thickness =0.79 mm.)
0.280	1.8	1.0	0.370	91.2	91.5
0.290	10.4	7.1	0.380	91.4	91.5
0.300	30.9	25.4	0.390	91.5	91.5
0.310	55.0	50.2	0.400 to 0.900	91.5	91.5
0.320	73.3	70.3	0.950	91.5	91.0
0.330	83.5	82.0	1.000	91.5	90.3
0.340	88.8	87.5	1.050	90.8	89.0
0.350	90.3	90.0	1.100	90.6	88.4
0.360	91.0	91.2			

TABLE 4.—*Transmission measurements for the infrared spectral region made on sample of glass from two Eppley pyrheliometer bulbs. Measurements taken from spectrograms obtained with a Perkin-Elmer double-beam infrared recording spectrophotometer by National Bureau of Standards*

Wave length (microns)	Transmittance (percent)		Wave length (mircons)	Transmittance (percent)	
	Bulb No. 1	Bulb No. 2		Bulb No. 1	Bulb No. 2
1.1	89.4	90.5	3.85	65.7	50.9
1.2	89.6	90.6	3.9	66.2	60.4
1.3	89.7	90.5	3.95	66.6	60.8
1.4	89.9	90.4			
1.5	89.9	90.4	4.0	66.7	61.0
1.6	89.9	90.4	4.05	66.8	61.0
1.7	89.9	90.6	4.1	66.5	60.3
1.8	89.9	90.6	4.15	64.9	58.9
1.9	89.9	90.6	4.2	62.7	56.3
			4.25	62.2	55.9
2.0	89.8	90.5	4.3	61.6	55.7
2.1	89.7	90.3	4.35	56.1	48.0
2.2	89.7	90.2	4.4	49.2	39.7
2.3	89.7	90.2	4.45	43.9	34.4
2.4	89.7	89.9	4.5	37.5	27.7
2.5	89.6	89.7	4.55	31.7	22.2
2.6	89.4	89.4	4.6	26.1	17.3
2.7	89.1	89.4	4.65	21.3	13.3
2.75	86.7	86.2	4.7	17.8	10.9
2.8	76.7	73.7	4.75	14.8	7.3
2.85	72.8	68.6	4.8	13.8	6.5
2.9	72.1	68.0	4.85	13.2	5.6
			4.9	12.7	5.0
3.0	71.8	68.0	4.95	12.0	4.4
3.1	72.0	68.2			
3.15	71.9	67.9	5.0	8.9	3.5
3.2	71.1	66.6	5.05	6.8	2.4
3.25	70.0	65.1	5.1	4.3	1.8
3.3	69.0	63.3	5.15	2.4	1.0
3.35	67.7	61.9	5.2	1.8	.6
3.4	66.6	61.2	5.25	1.4	.5
3.45	65.6	60.3	5.3	1.0	.4
3.5	65.0	59.7	5.35	.6	.2
3.55	64.7	59.4	5.4	.4	.1
3.6	64.6	59.1	5.45	.3	.1
3.7	64.6	59.0	5.5	.2	.0
3.75	64.6	59.0	5.6	.1	.0
3.8	65.0	59.3	5.7	.0	.0

The tests were made by Ralph Stair, Physicist, of the Radiometry Laboratory of the Bureau of Standards, who signed the letter of transmittal.

The table enclosed with the letter is shown here as table 3. Data were extracted from infrared spectrograms

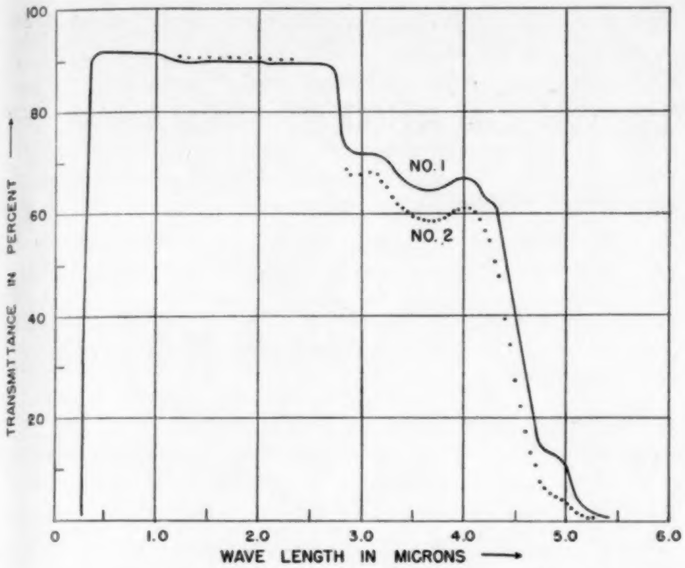

Figure 10.—Transmittance of glass samples from pyrheliometer bulbs No. 1 and No. 2, as a function of wavelength. From tests by National Bureau of Standards.

of the Perkin-Elmer spectrophotometer, corrected for zero and for 100 percent drift. These data appear in table 4. Ordinate values of sample 1 were multiplied by 1.02 as suggested in the letter of transmittal. Figure 10 is a graph based on data from tables 3 and 4.

CONCLUSIONS

The tests described suggest that the ultimate accuracy of the pyrheliometer may be more closely approached by considering the cosine and temperature effects. They also provide a partial basis for estimating accuracy of measurements "in the field," where such calibrations are ordinarily unavailable, and where the cost in time and money of obtaining such calibrations and applying them routinely might not justify their use. They indicate that rain droplets do not influence the readings appreciably; they also indicate that measurements taken with the pyrheliometer in the vertical plane are about five percent too low. The Bureau of Standards spectral transmission data indicate that transmission of the glass cover is practically constant over substantially all of the solar radiation spectrum.

ACKNOWLEDGMENTS

As explained in the text, the data on which this report is based were from two sources: (1) National Bureau of Standards Radiometry Section of the Division of Optics, Dr. Curtis J. Humphreys and Ralph Stair, Physicist, and (2) Weather Bureau Instrument Division, by Mr. Norman Foster and the writer. The assistance of Mr. Ruben Guenthner of the Instrument Division is gratefully acknowledged, as are the numerous useful suggestions by S. Fritz of the Weather Bureau Scientific Services Division. We are also indebted to Mr. Raymond Teele of the Bureau of Standards, whose staff checked the standard lamps.

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THE WEATHER AND CIRCULATION OF AUGUST 1951[1]

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The general circulation of the Northern Hemisphere (fig. 1) for August was dominated by four major full-latitude waves, each extending from the polar region to the subtropics. The four major trough lines can be seen on figure 1; one along the east coast of North America, a second along the west coast of Europe and Africa, a third through central Asia, and the fourth extending southwestward from the Arctic Ocean through the Bering Sea and the western Pacific Ocean. Over the Eastern Hemisphere these waves had a larger amplitude than over the Western Hemisphere, where the circulation in middle latitudes was characterized by a zone of relatively strong flat westerlies.

To the south of this zone of strong westerlies the subtropical high pressure cells appeared as rather narrow elongated east-west ridges. The Pacific high pressure belt extended from California to China, while the elongated "Bermuda High" reached as far west as Lower California, with one center in Louisiana and the other in the central Atlantic. The easterly circulation around the southern periphery of this elongated "Bermuda High"

[1] See charts I-XV following p. 167, for analyzed climatological data for the month.

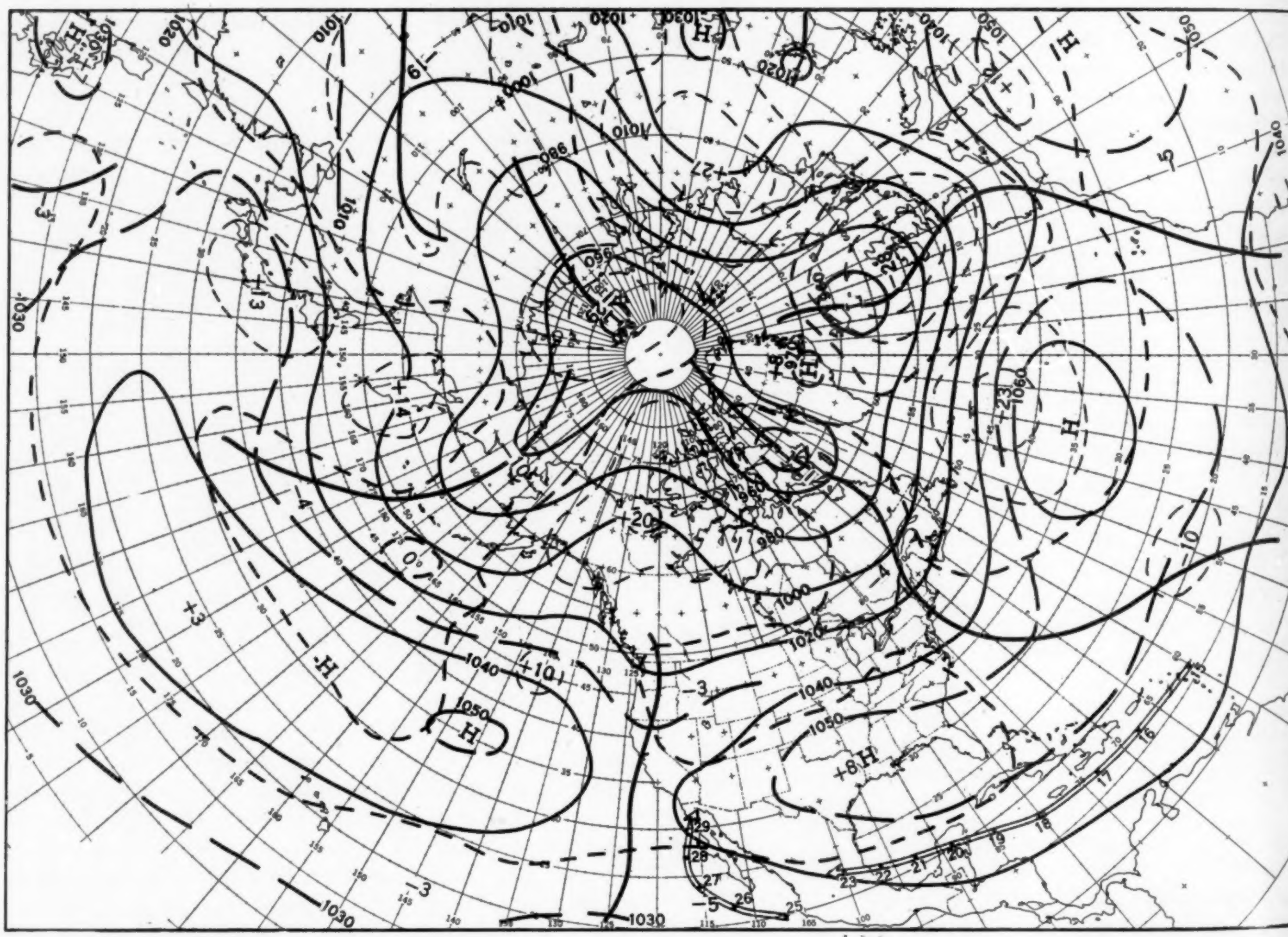


FIGURE 1.—Mean 700-mb. chart for the 30-day period July 31–August 29, 1951. Contours at 200-ft. intervals are shown by solid lines, intermediate contours by lines with long dashes and 700-mb. height departures from normal at 100-ft. intervals by lines with short dashes with the zero isopleth heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines. Open arrows in Caribbean and near Lower California indicate hurricane paths.

swept in an uninterrupted zone across the Atlantic and the Caribbean into northern Mexico and the southwestern part of the United States. A similar broad belt of easterly trade winds prevailed over the Pacific Ocean.

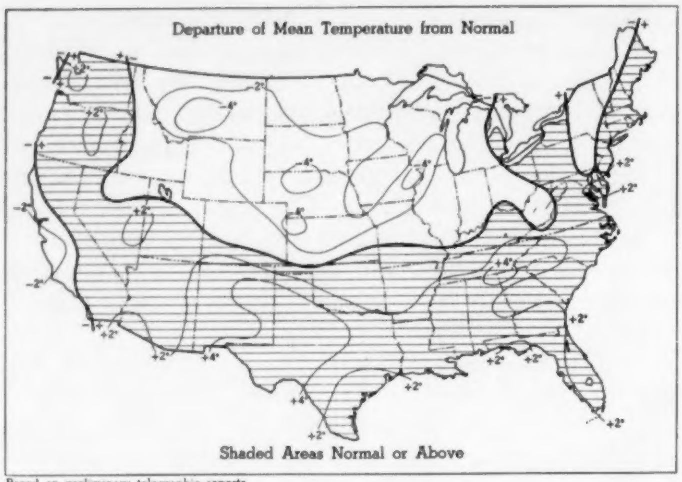
On figure 1 it may be noted that between the two cells of the subtropical high pressure belt there was a minor trough off the west coast of the United States, extending northward into British Columbia. To the north of this weak low-latitude trough a strongly developed ridge was crested in northwestern Canada. This strong ridge, oscillating in position between the Gulf of Alaska and northwestern Canada, led to an abnormally large number of cold air outbreaks in the northern United States during the 1951 summer. Nowhere else in the Northern Hemisphere did the general circulation exhibit this out-of-phase relationship between a ridge to the north and a trough to the south. Therefore, nowhere else on the map was there such a zone of marked confluence as was found along the northern border of the United States. The principal effect of this confluence was to intensify the meridional temperature gradient and increase the speed of the westerly winds across the northern United States and to the east over the Atlantic. As a result, the monthly mean storm track for August was that of the typical "Northern Pacific" type storm [1]. Most of the cyclones (Chart X) traversed the area on figure 1 where negative mean height anomalies appear. (Note 30-foot anomaly center in western Montana.) Behind each individual storm which moved along this track, cold air rushed southward from central Canada. However, the greater part of this cold air was swept eastward out to sea by the powerful westerlies before it could penetrate the southern United States. The storm tracks on Chart X show that no storms of the "Texas type" or "East Gulf type" were observed during this month.

The complete absence of any strong cold air outbreaks from the north, associated with the presence of a pronounced ridge aloft, produced one of the most prolonged heat waves ever experienced in the southern United States. Normally during summer occasional easterly waves bring cloudiness, precipitation, and relatively cool temperatures to the Gulf States. During this month, however, all easterly waves were displaced far to the south around the upper level ridge, leaving the Gulf States broiling in bright sunshine day after day (Chart VII). There was no respite because the upper level ridge, although not unusually intense, was remarkable for its great stability, varying little in position and magnitude from day to day.

Temperatures averaged from 4° to 6° above normal every week of the month throughout most of the west Gulf States. In many Texas cities above-normal temperatures were recorded every single day. Temperatures of 100° F., or more, were recorded in Texas on 29 days during August. In Dallas, the hottest day was August 17 when for 9 consecutive hours the temperature remained above the 100° F. mark. As of September 1 the temperature had climbed above 100° on 30 days in Dallas and on 94 days in the Rio Grande valley. Drought, the inevitable companion of extended summer hot spells, was prevalent throughout most of Texas. Presidio, with 0.06 inch of rain, experienced the driest August of its history. The warm dry air was by no means restricted to Texas, above-normal temperatures and deficient precipitation were reported over most of the area south of the principal storm track. (Charts I and III.)

North of this track the moist, cool weather which had characterized much of July persisted. The interaction of cool air from the north and warm air from the south resulted in less than usual sunshine, below-normal temperatures, and abundant precipitation through the Lake Region and the Plains from Kansas to the Canadian border. The mechanism causing this precipitation was similar to that which had produced the heavy rains in this region throughout the summer [2, 3]. The band of heaviest precipitation associated with the polar front moved gradually northward, giving floods in Kansas in late June and early July and more general rains across the northern United States in August. The effect of these rains in Iowa and in other nearby portions of the Corn Belt was to delay the maturation of the corn crop to such an extent that about 30 percent of the crop would be lost if the first killing frost occurred at its normal fall date.

The precipitation area in the Plains States merged to the southwest with another region of heavy rains, the lower Colorado River Basin of Arizona and California. Here the precipitation could be traced to the influence of two tropical hurricanes. The paths of these storms are shown on figure 1 and Chart X. The first hurricane, "Charlie," was initially sighted on August 15, just east of the Lesser Antilles. It moved in a nearly straight line around the periphery of the subtropical ridge into Mexico just north of Tampico. The stability of this ridge is illustrated by the closeness of the fit between the storm track and the mean flow pattern in this area (fig. 1). The moisture from this storm caused torrential downpours over Mexico during the last ten days of August; flooding there caused over 400 deaths. The heavy rains extended as far north as Brownsville, Tex., as the storm battered the east coast of Mexico. The tropical storm itself became dissipated over the land but the prevailing southeasterly winds carried the moisture from the hurricane across Mexico and over the mountains into the Pacific, where a new tropical cyclone developed off the coast. The circulation around this second disturbance dispersed the moisture, resulting in rain in California, Arizona, the southern tip of Nevada, western New Mexico, and to the northeast. Portions of the desert areas of the Southwest were flooded for several days, the rainfall there exceeding the heaviest observed in the past 11 years. (A



Based on preliminary telegraphic reports

Figure 2.—Departure of mean temperature from normal for the summer season (June, July, August) 1951. (From U. S. Weather Bureau *Weekly Weather and Crop Bulletin* for week ending September 18, 1951.)

more detailed discussion of these heavy rains can be found in the article by J. A. Carr, p. 163 of this issue.)

In retrospect, the general circulation over North America differed in August only slightly from what it had been in June and July [2, 3]. The strong ridge in northwestern Canada and the Gulf of Alaska, a dominant feature of the summer season, and the strong ridge extending east-west along the southern border of the United States interacted to produce rather similar weather patterns each month throughout the summer. As a result the chart showing the temperature anomaly distribution in the United States in August (Chart I–B) closely resembles the corresponding chart for the summer as a whole (fig. 2).

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THE RAINS OVER ARIZONA, AUGUST 26–29, 1951

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INTRODUCTION

On August 26, 1951, showers and thunderstorms occurred over southern Arizona bringing to a temporary end a prolonged period of above normal temperatures. During the succeeding three days the area of precipitation expanded as the thunderstorms gave way to a more steady type of rainfall. Low maximum and minimum temperatures were noted during the rain period with some stations reporting record, or near record, low maximum temperatures.

This article will present the results of a brief investigation into the causes of this unusual weather.

MAJOR CIRCULATION INFLUENCE

The rain over Arizona presents an interesting example of the connection between the weather at one point and the weather at another; in this instance, the rain in Arizona and the heat in Texas.

Throughout August very dry weather prevailed over Texas as the land lay in the grip of one of the most persistent periods of heat in its history. Temperatures, over the State, ranged from the nineties to the hundreds throughout the entire month. Under clear skies the air was heated to high levels and helped maintain a warm, circular High, aloft, over west Texas and the west Gulf region. Toward August 25, 1951, this High increased in size to the extent that it covered the entire Gulf and the ocean areas adjacent to the west coast of Mexico [1].

At the surface the air moved over the warm waters of the Gulf of Mexico absorbing moisture as it went. Over the middle and northern half of the Gulf the air moved inland over Mexico curving anticyclonically as it approached the hills and mountains of the Sierra Madre Range (in northern Mexico, just west and parallel to 106° W. Long.). In time the anticyclonic curvature brought the air northeastward, on a downslope path, across New Mexico and Texas.

However, west of the Sierra Madre Range a different situation developed. Judging by the flow, some air from the lower Gulf of Mexico and air over the tropical waters off Central America joined forces to the west of the Pacific coast of Mexico. These winds, under the same influence as the air to the east of Mexico, moved poleward curving anticyclonically with time (fig. 1). Thus, we find air becoming more moist during a long fetch over warm waters, picking up some of the moisture associated with the hurricane southwest of Lower California, acquiring additional moisture as it channeled northward, through the Gulf of Lower California, and finally, arriving at Yuma where the first topographical feature intervened.

THE ROLE OF TOPOGRAPHY

Once on land the air continued on the anticyclonic path, as directed by the pressure pattern, but was deflected somewhat to the left of the free air path by the influence of the terrain.

The land surface is lowest in the region of Yuma from where it rises to the east and north. To the east and northeast of Phoenix the land rises abruptly to form the Colorado Plateau. The effect of the land formation was such that the air moved northeastward over rising ground without too much interference until the western fringes

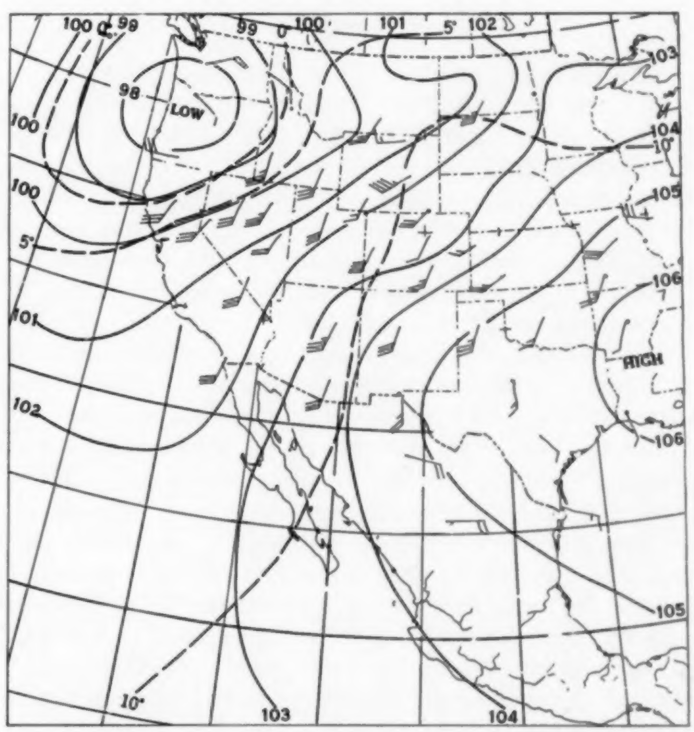


Figure 1.—700-mb. chart for 1500 GMT, August 29, 1951. Contours (solid lines) at 100-foot intervals are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are at intervals of 5°C. Barbs on wind shafts are for speeds in knots (pennant=50 knots, full barb=10 knots, half barb=5 knots).

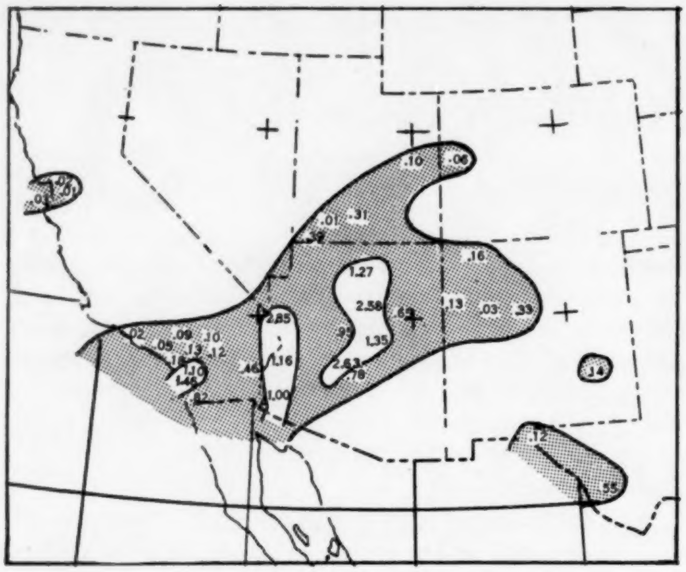


FIGURE 2.—24-hour precipitation ending 1230 GMT, August 29, 1951 (Shaded=Trace or <1 inch, encircled white=1 inch or more).

of the Colorado Plateau were reached. With this obstruction in its path, the air, still trying to move northeastward, was deflected more to the north of its path in the Phoenix-Prescott region. This idea is supported by the reported southeast surface winds, during the rain period, at these stations.

SURFACE EFFECTS

Rainfall began on the 26th, as moist winds moved inland along the southwest border. The combination of hot ground, strong solar heating, and a low level of condensation in the rising air set the stage for the numerous thunderstorms which were reported by various stations. By late evening of the same day the strong convective stage was passed as was indicated by the absence of reports of thunderstorms and the frequent observation of showers and steady rain.

The rains spread across Arizona in a discernable pattern so arranged that the long axis of the heaviest precipitation pattern was orientated northeastward from the southwest border of the State, and then north across Flagstaff (fig. 2). Such an orientation suggests the topographical influences previously discussed. The heaviest falls were recorded along the axis and in, or near, the center of the line (near Flagstaff). Tucson was to one side of the main flow as revealed by the 3-day total of only 0.62 inch, which fell in 1 day. A second axis of flow existed on the 27–28th in the Yuma to Needles (Calif.) region. A tabulation of rainfall amounts and related data is presented in table 1.

When the month came to a close, Phoenix had received a total of 5.33 inches, marking the month as the wettest August in the 56-year history of the station. The rains of the 26th to 29th yielded the greatest total ever recorded

TABLE 1.—*24-hour totals of rainfall for selected stations in Arizona, Aug. 26–29, 1951 (with comparative data)**

Station	Station elevation (above MSL)	Average monthly precipitation	24-hour total				Storm total	Previous record 24-hour total
			Aug. 26	Aug. 27	Aug. 28	Aug. 29		
	Feet	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*
Flagstaff	6,993	2.83	T	.10	2.28	1.62	3.00	1.92
Payson	5,000	2.15	2.00	2.12	2.12	1.53	7.77	.96
Phoenix	1,083	.96	.03	2.43	.84	.50	3.80	2.17
Prescott (WBAS)	5,014	2.82	.01	T	1.51	1.06	2.58	2.11
Tucson	2,558	2.17	T	.62	T	-------	.62	1.50
Winslow	4,880	1.34	.07	.19	.94	.10	1.30	1.10
Yuma	203	.57	.05	.15	.68	.25	1.13	4.01

*Source—U. S. Weather Bureau, *Station Meteorological Summary* (for stations shown), August 1951.

during the month of August. Tucson had its heaviest total for August since 1946. At Payson a 43-year record for greatest total rainfall for any month was broken by the August total of 10.38 inches. Flagstaff reported the rain on the 28th was the greatest of record for any day in August.

The rain plus a thick layer of clouds produced interesting effects upon the temperature readings. Maximum readings dropped markedly under the influence of evaporation of falling rain, evaporation of rain from the ground surface, and cooling of the air by passage of cold rain through the lower layers of the atmosphere. These factors, added to a 3-day period of 9 to 10 tenths cloud cover over a large portion of the State, helped maintain relatively low temperatures.

At Yuma, for instance, the month was consistently above normal with maximum temperatures above 100° F. for the first 25 days of the month. From a high of 110° on the 25th to a high of only 80° (27th) was a sharp change for the residents, especially when it is recalled that the humidity on the latter date was quite high. Phoenix reported a maximum of 73° on the 27th after a period of 22 consecutive days of 100° or above. In fact the maxima of 73° (27th) and 76° (29th) were the lowest ever observed at Phoenix in any August. A tabulation of the maximum and minimum temperatures is presented in table 2.

TABLE 2.—*Maximum and minimum temperatures for selected stations in Arizona, August 25–31, 1951**

Station	Maximum temperature (° F)							Minimum temperature (° F)						
	Aug. 25	Aug. 26	Aug. 27	Aug. 28	Aug. 29	Aug. 30	Aug. 31	Aug. 25	Aug. 26	Aug. 27	Aug. 28	Aug. 29	Aug. 30	Aug. 31
Flagstaff	80	80	63	58	57	69	73	37	44	46	51	49	44	38
Payson	93	86	63	70	63	77	82	58	57	56	55	50	47	48
Phoenix	104	100	73	83	76	92	93	76	72	68	68	67	65	69
Prescott (WBAS)	89	86	72	69	66	77	80	51	56	54	55	52	47	46
Tucson	100	88	73	86	88	91	94	76	70	66	71	71	68	63
Winslow	94	90	73	66	74	83	84	57	60	59	55	55	49	52
Yuma	110	99	80	87	93	95	100	72	73	72	71	70	71	72

*Source—U. S. Weather Bureau, *Station Meteorological Summary* (for stations shown), August 1951.

FEATURES OF THE SURFACE MAPS

A survey of the surface weather maps for August 26 to 30 yielded little of value as an aid to the explanation of the weather. Figures 3, 4, and 5 illustrate the relatively unchanging features of the surface pressure over the southwestern States. Two interesting features did come to light, however. The first, and not too surprising, effect was the disappearance of the thermal Low over Arizona, especially on the 27th. The second feature was a westward migration of a High cell which on August 26 had been centered over New Mexico. As the rain area spread, the High moved toward eastern Arizona where it persisted and grew in size till near the end of the period. This High was related to the western end of the upper level High which on the 27th extended from Florida to New Mexico, roughly parallel to 36° N. Lat.

To some extent the western periphery of the High was "fictional." As the temperatures dropped within the storm area, they soon reached values lower than the readings at stations outside the rain area. With such a situation two mountain stations, one in the rain and one outside the rain area, at the same altitude and observing approximately the same station pressure, but with a difference of 20° to 30° between their surface temperatures would report entirely different sea level pressure readings after reducing their station pressures. This, of course, would result from one station calculating a higher sea level pressure by using a relatively low value for the mean temperature of the air column from the station level to sea level.

The apparent spreading of the western side of the High wiped out the form of the heat Low. When the rains ended and solar heating once more took over, the edge of the High retreated from the southwest portion of the State while the center itself moved north toward the Utah border.

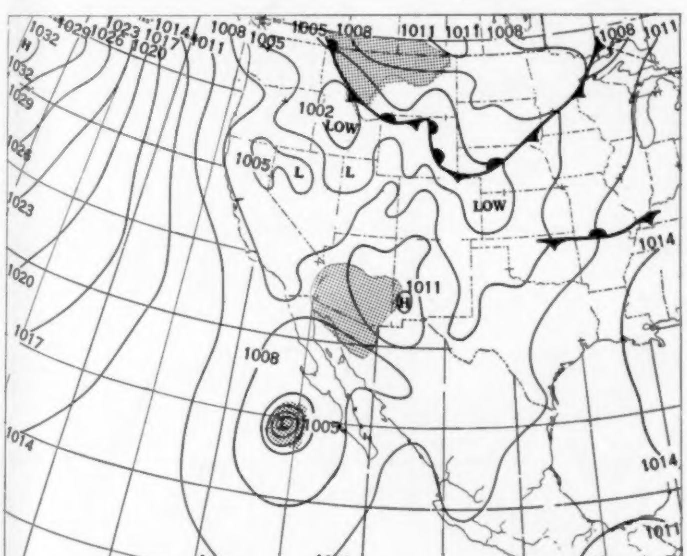


Figure 3.—Surface weather chart for 1830 GMT, August 27, 1951. Shading indicates areas of active precipitation.

LOWER TROPOSPHERE MOISTURE AND TEMPERATURE DISTRIBUTION

Graphs showing the vertical distribution of moisture at Phoenix were prepared, with figure 6 showing the period of increasing moisture. The curve for August 25 shows the moisture content on a dry day during which the temperature rose to 104° F. under a cloudless sky. The winds aloft were southwest as was to be expected of the return flow of the upper level High. The significant point on this curve is the layer of moist air centering around 700 mb. The curve for the 26th shows a large

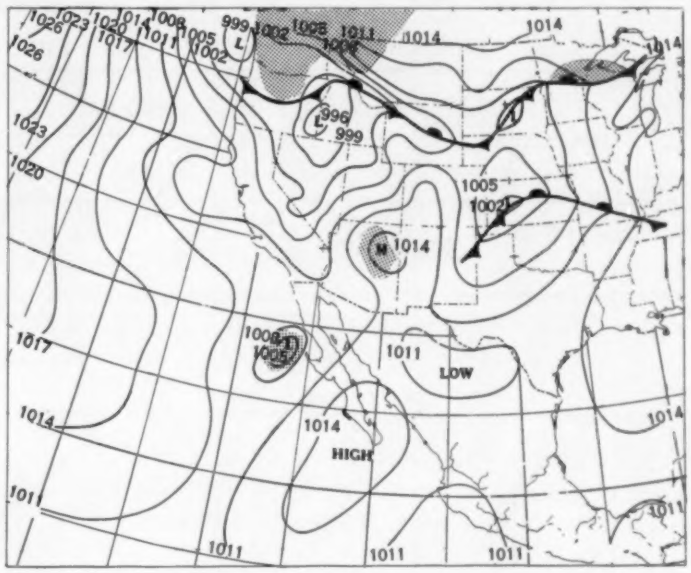


Figure 4.—Surface weather chart for 1830 GMT, August 28, 1951.

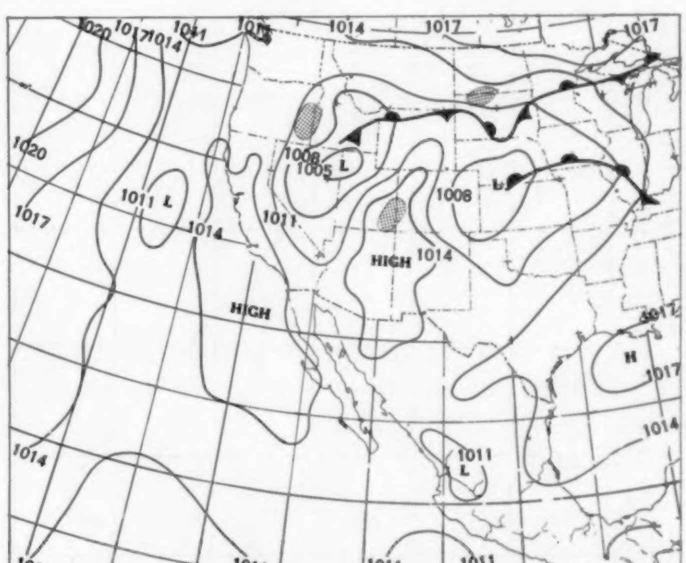


Figure 5.—Surface weather chart for 1830 GMT, August 29, 1951.

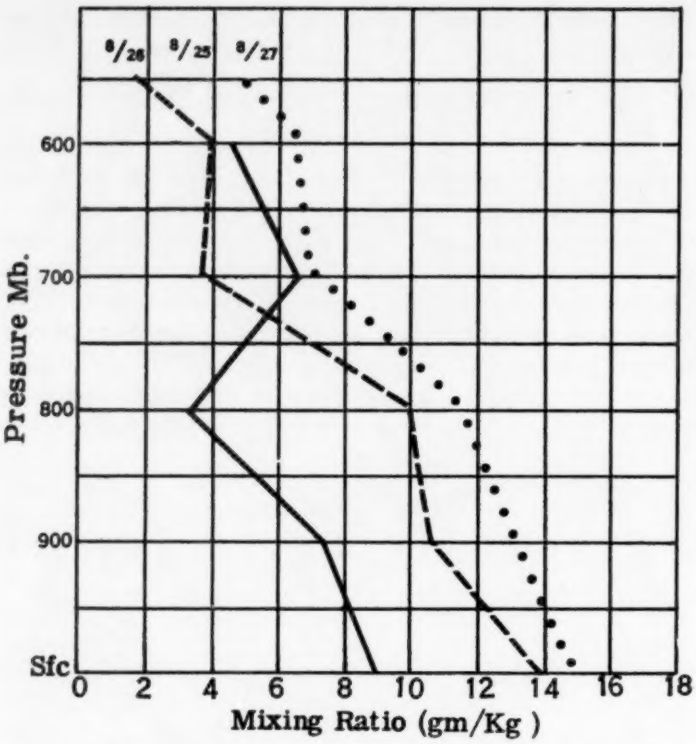


FIGURE 6.—Moisture soundings (grams of water vapor/kilogram of dry air) at Phoenix, Ariz., 1500 GMT, August 25 (solid line), August 26 (dashed line), August 27 (dotted line), 1951.

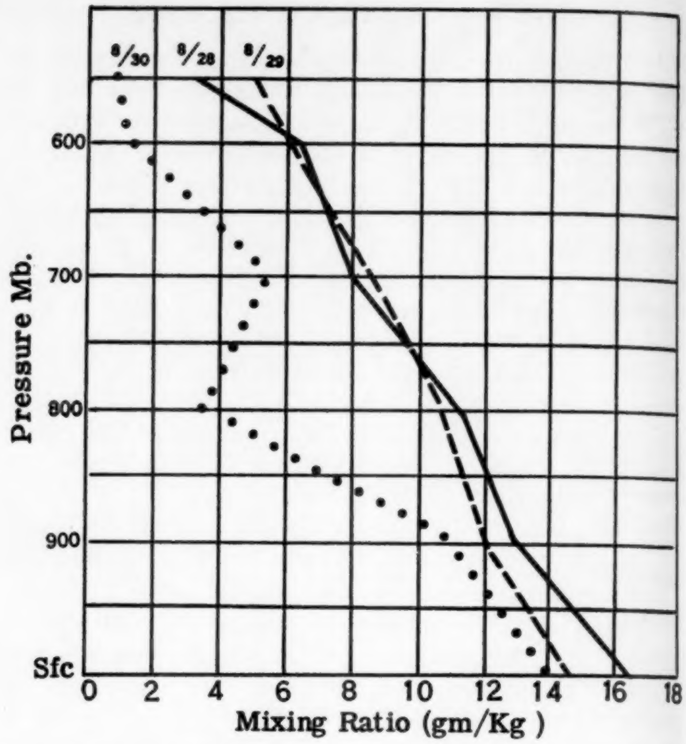


FIGURE 8.—Moisture soundings (grams of water vapor/kilogram of dry air) at Phoenix, Ariz., 1500 GMT, August 28 (solid line), August 29 (dashed line), August 30 (dotted line), 1951.

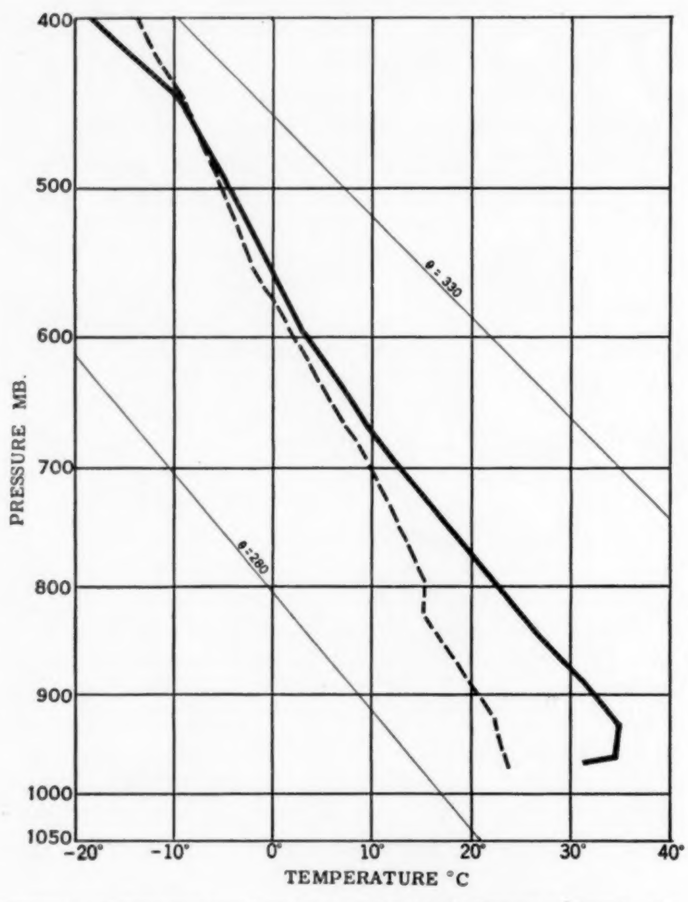


FIGURE 7.—Temperature soundings (on a pseudo-adiabatic diagram) at Phoenix, Ariz., 0300 GMT, August 25 (solid line), August 27 (dashed line), 1951.

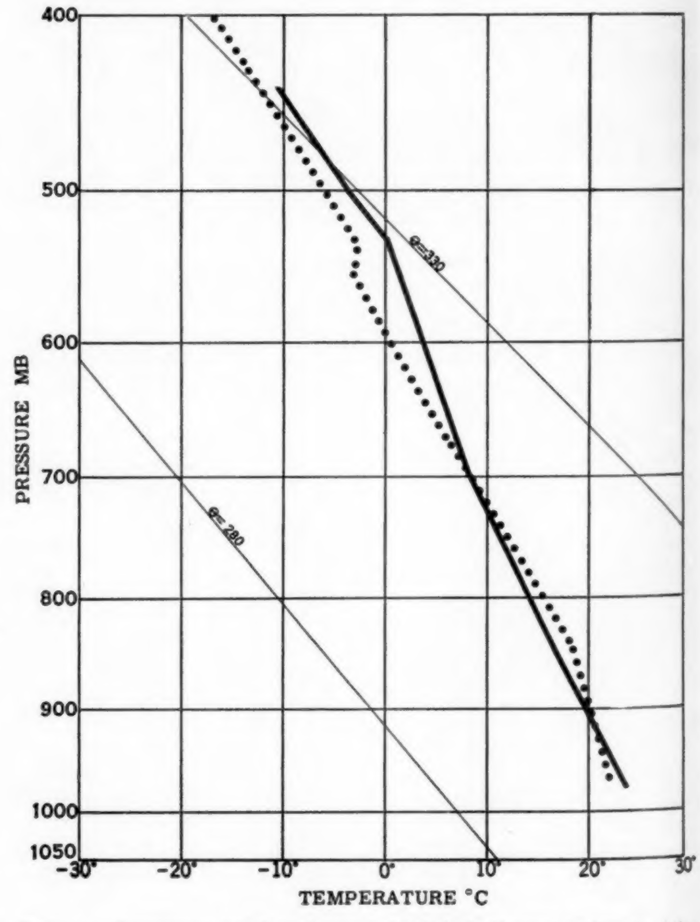


FIGURE 9.—Temperature soundings (on a pseudo-adiabatic diagram) at Phoenix, Ariz., 0300 GMT, August 29 (solid line), August 30 (dotted line), 1951.

24-hour increase from the surface to approximately 800 mb. with some decrease from 730 to 550 mb. Over the next 24 hours, the curve (27th) shows increases from the surface to 550 mb., with the greatest increase centering around 700 mb. and with a second maximum from 600 to 550 mb. Comparing the curves for August 25 and 27, the 48-hour change shows a region of maximum moisture increase from 900 to 770 mb. with a second maximum from the surface to 900 mb. In other words, the greatest increase of moisture was in the lower levels. This fits in with the other evidence previously presented.

As shown in figure 7, the Phoenix temperature soundings for the same 2 days (25th and 27th) indicate that the air on August 25 was conditionally unstable from the surface to 680 mb. where it became stable with respect to the moist adiabatic lapse rate. It is interesting to note the development of an inversion at the surface at 0300 GMT, on the 25th. In 48 hours the change of air mass was reflected by the moist adiabatic conditions from the surface to near 550 mb. At the same time strong cooling had taken place as indicated by the separation of the two curves from 800 mb. down to the surface.

The period of decreasing moisture at Phoenix is shown by the curves of figure 8. The curves of August 28 and 27 (fig. 6) show close agreement as conditions in the free air were not too different during the interval. In the following 24 hours, the curve of the 29th shows the moisture content of the air had decreased slightly from the surface to 750 mb. without any particularly significant change above 750 mb. However, the curve of August 30 indicates a strong drop off of moisture had taken place at all levels from the surface to 550 mb. The smallest change was found from the surface to 900 mb., which is to be expected in light of the 3-day soaking rain and some flooding over the land. The curve shows the greatest influx of drier air took place at about 800 mb.

The curve of August 30 seems to have been approaching the same shape and values as the "pre-rain" curve of the 25th, although the moisture values were still generally higher.

The temperature soundings for August 29 and 30 (fig. 9) show a 24-hour change to warming between 920 and 720 mb. and a cooling above to 400 mb. Apparently on August 30, the heat from the sun was being spent, mostly, in evaporating water from the earth's surface. This is indicated by the slow return of the moisture curve to the values preceding the rain.

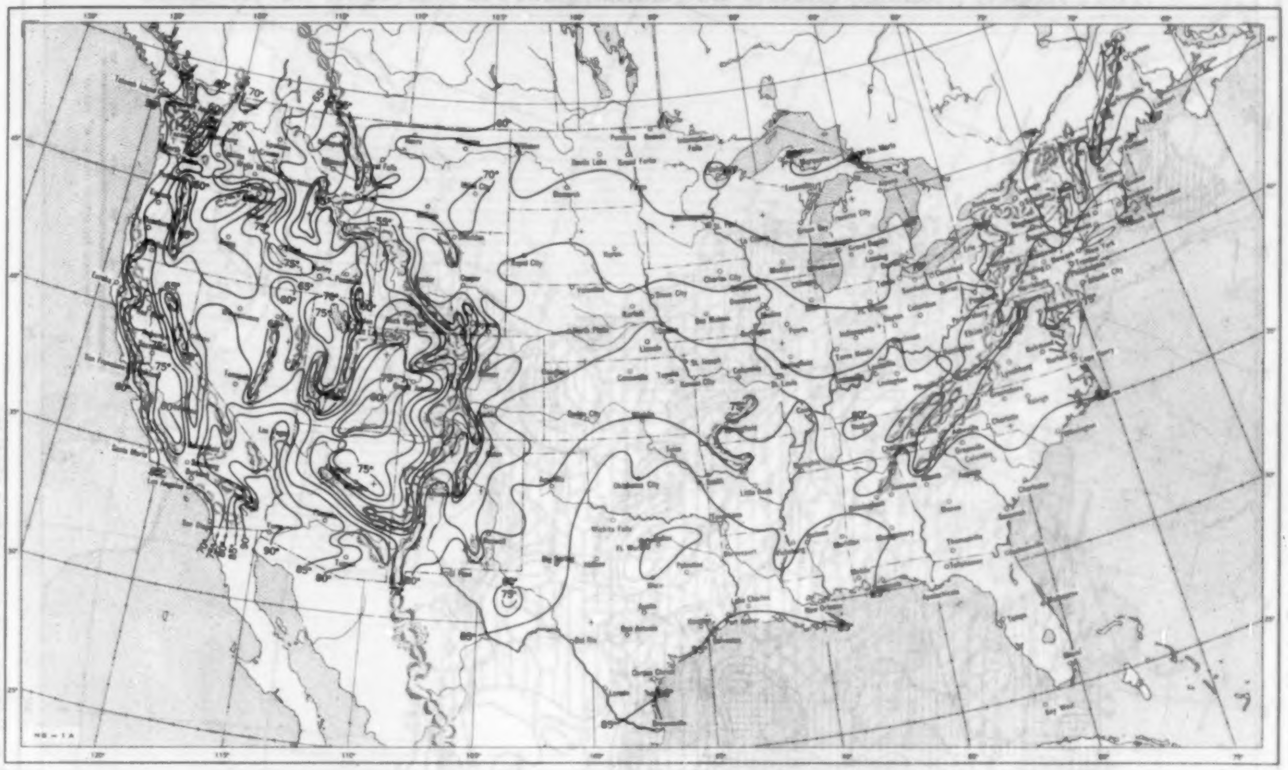
While the rains continued in Arizona the upper circulation remained essentially unchanged until the 29th. On this date a deepening upper level Low (fig. 1) over Washington and Oregon changed the circulation along the Pacific Coast. The air that now arrived over Arizona, like the air it displaced, had moved long distances over water. However, the water, this time, was quite a bit colder and consequently the cold air from the more northern latitudes possessed a more stable lapse rate. The stable air with lower moisture content moved in over the Southwest and brought clearing weather that finally enabled the temperature to return to the more normal 100° readings.

REFERENCE

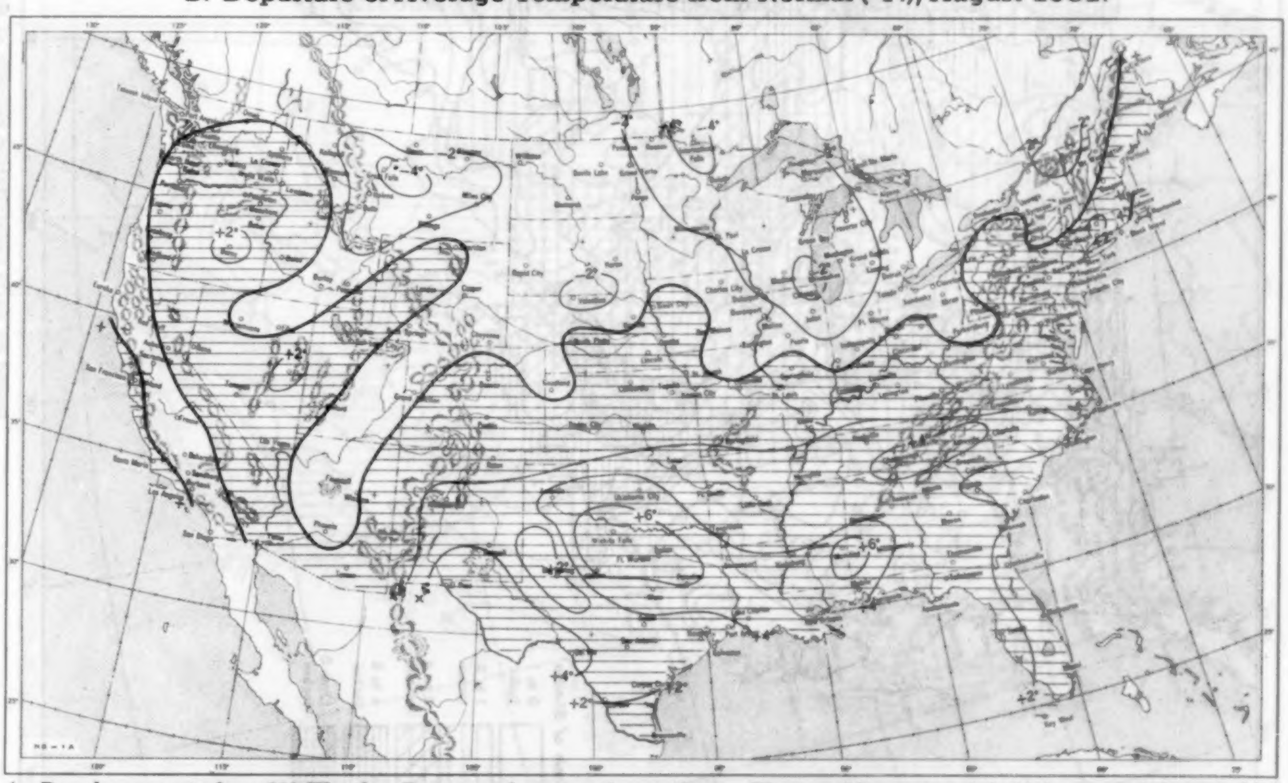
1. V. J. Oliver, "The Weather and Circulation of August 1951," *Monthly Weather Review*, vol. 79, No. 8, August 1951, pp. 160–163.

U. S. GOVERNMENT PRINTING OFFICE: 1951

Chart I. A. Average Temperature (°F.) at Surface, August 1951.



B. Departure of Average Temperature from Normal (°F.), August 1951.

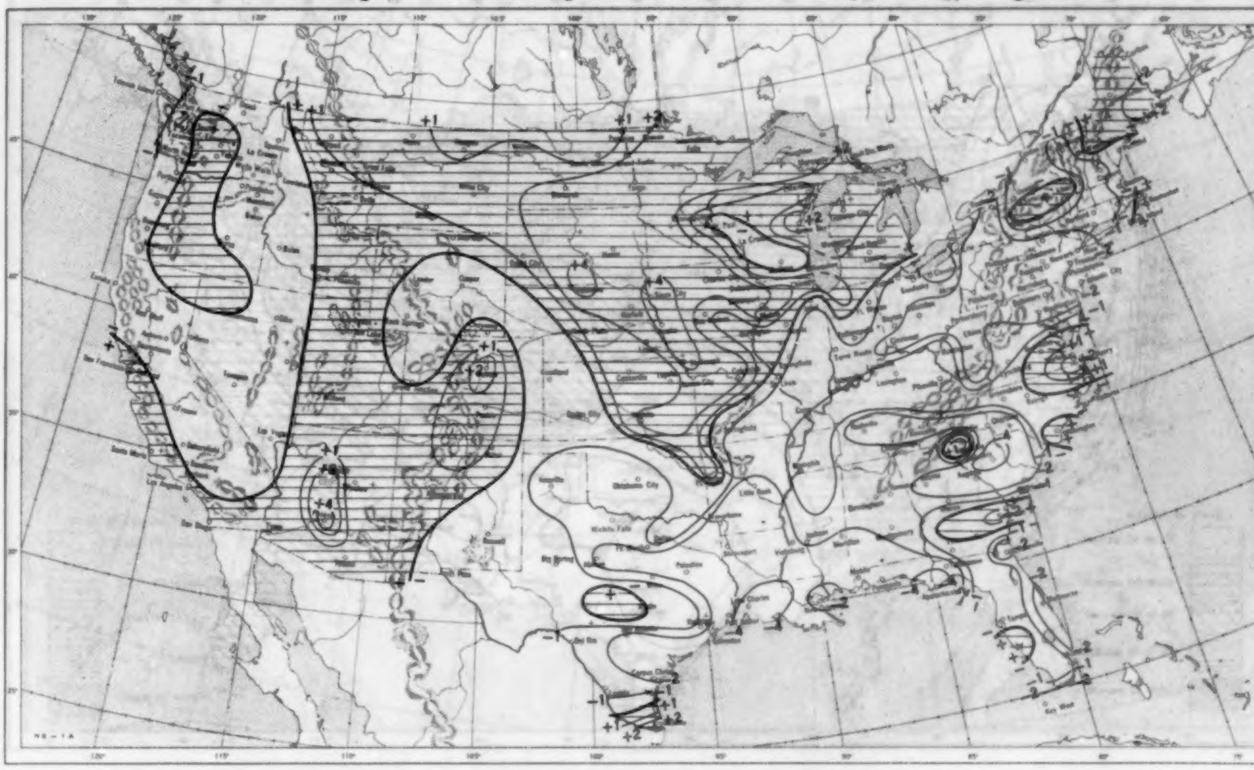


A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), August 1951.

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

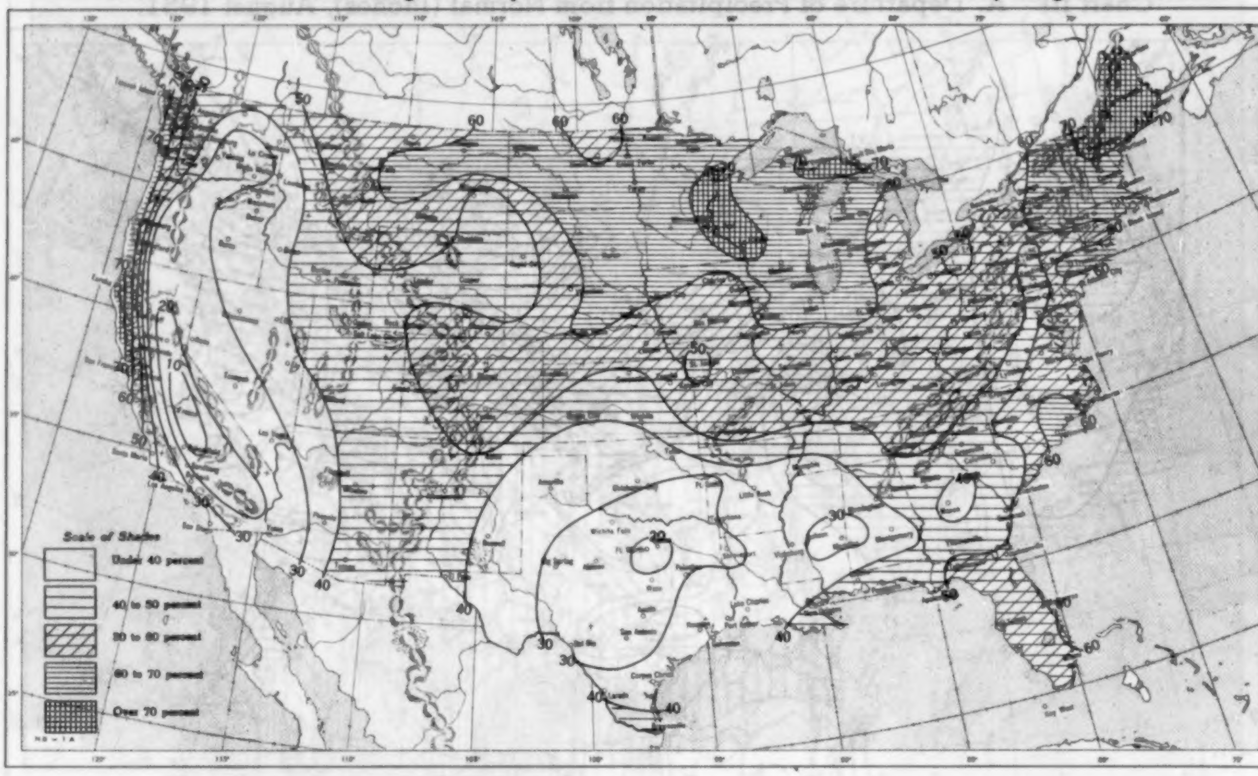
Chart III. A. Departure of Precipitation from Normal (Inches), August 1951.



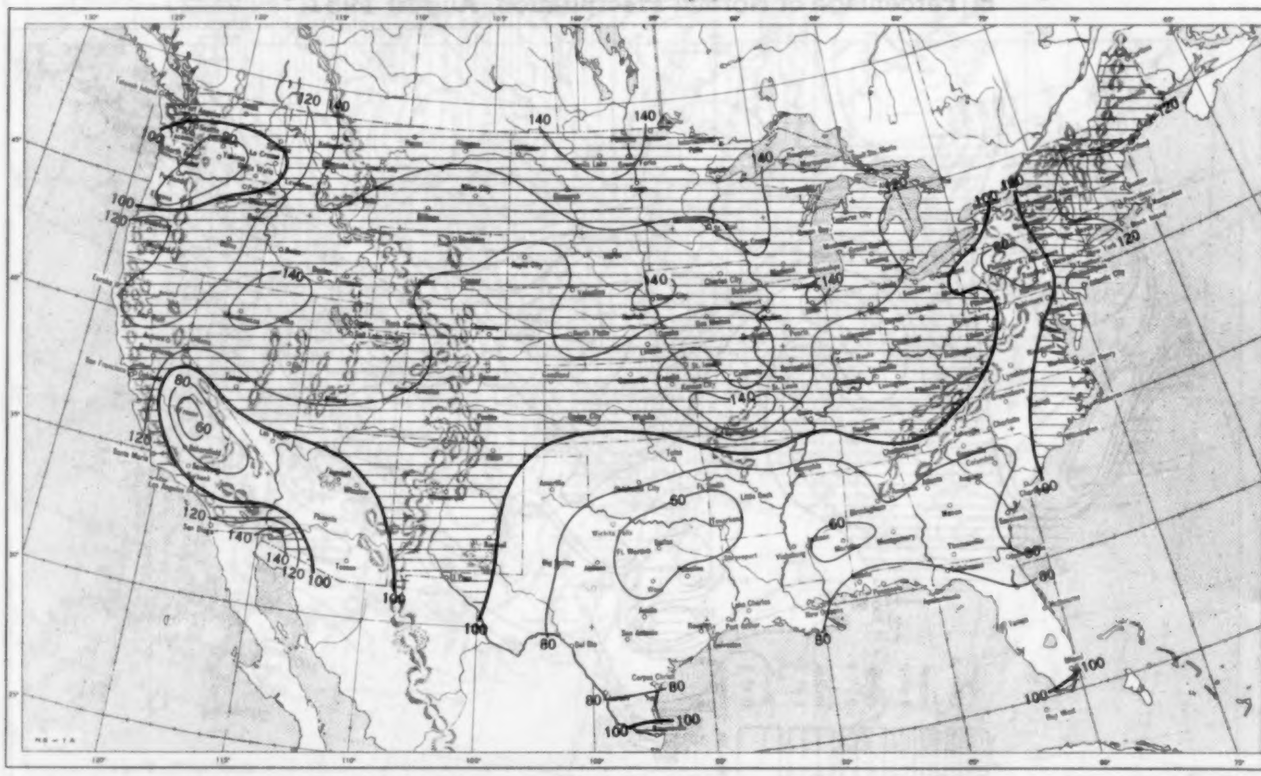
B. Percentage of Normal Precipitation, August 1951.

Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, August 1951.

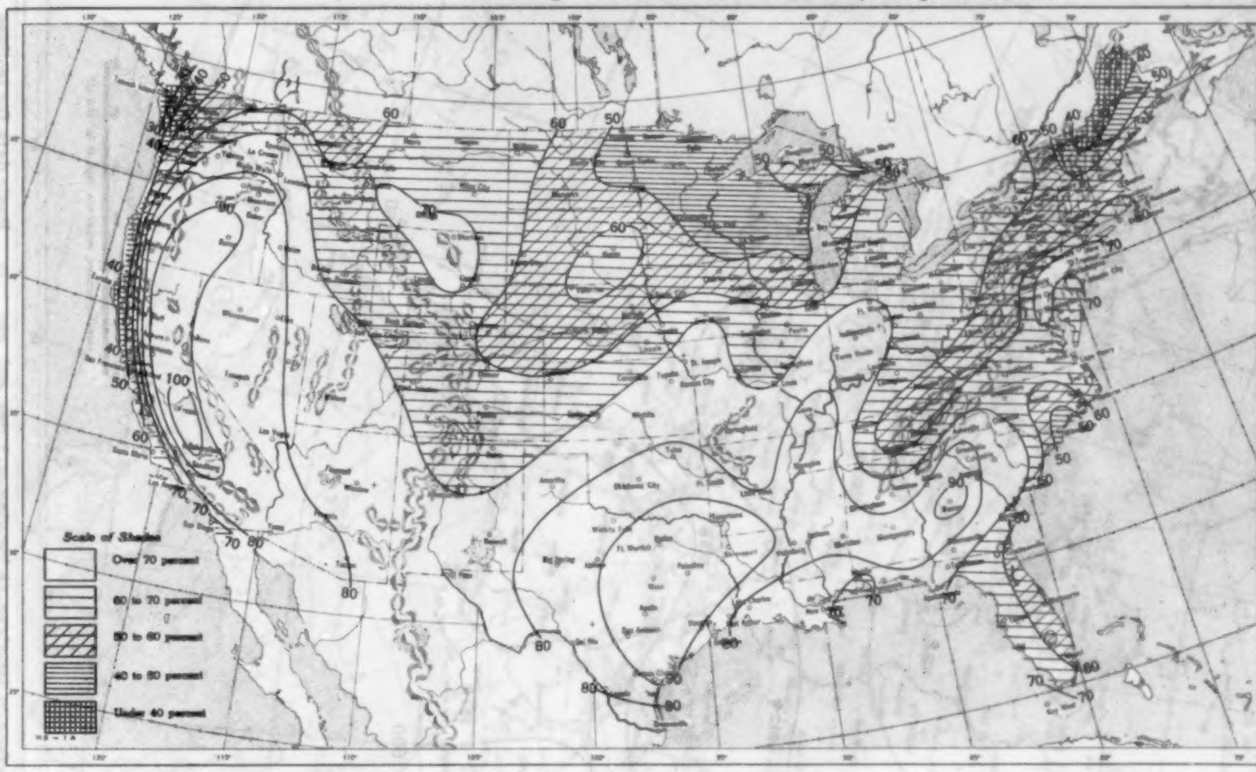


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, August 1951.

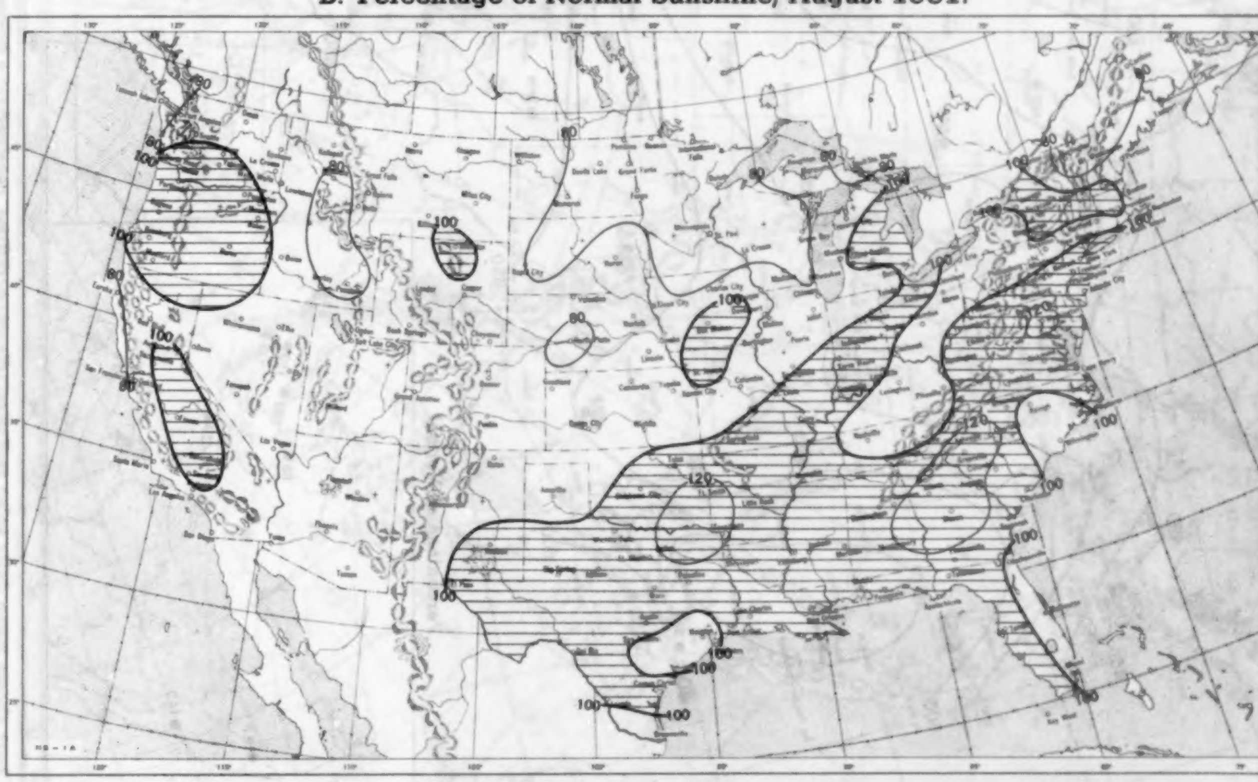


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, August 1951.



B. Percentage of Normal Sunshine, August 1951.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, August 1951. Inset: Percentage of Normal Average Daily Solar Radiation, August 1951.

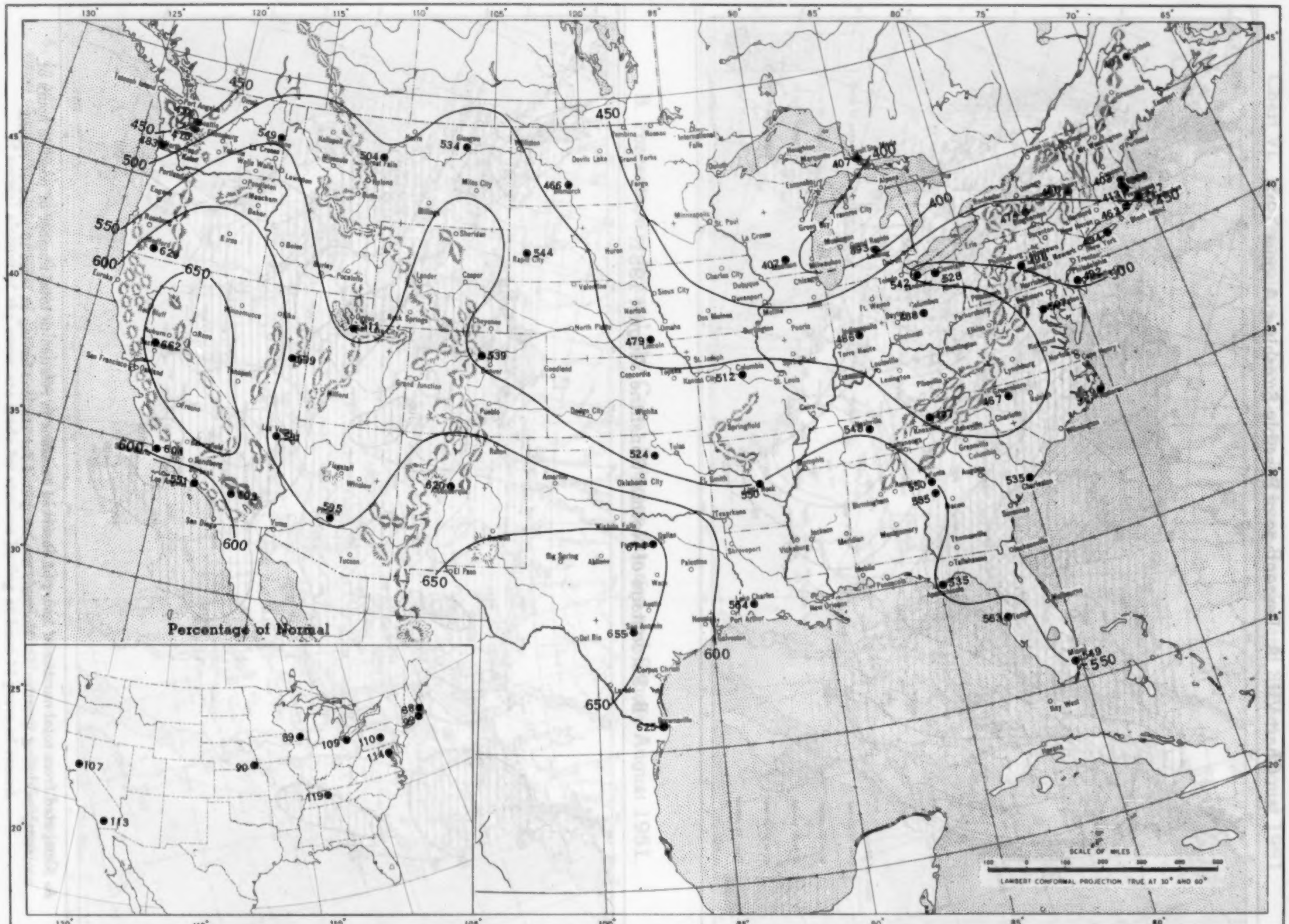
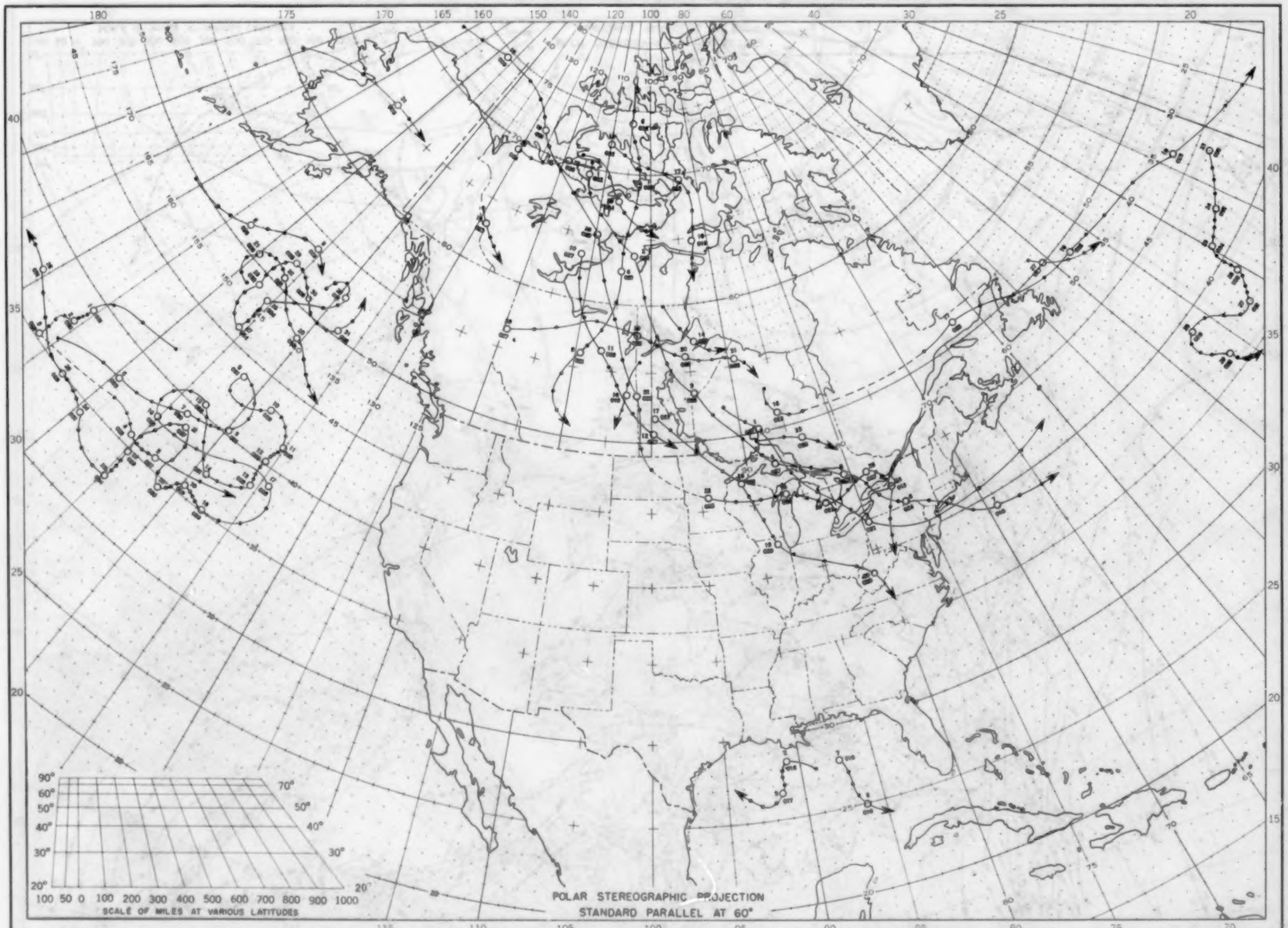


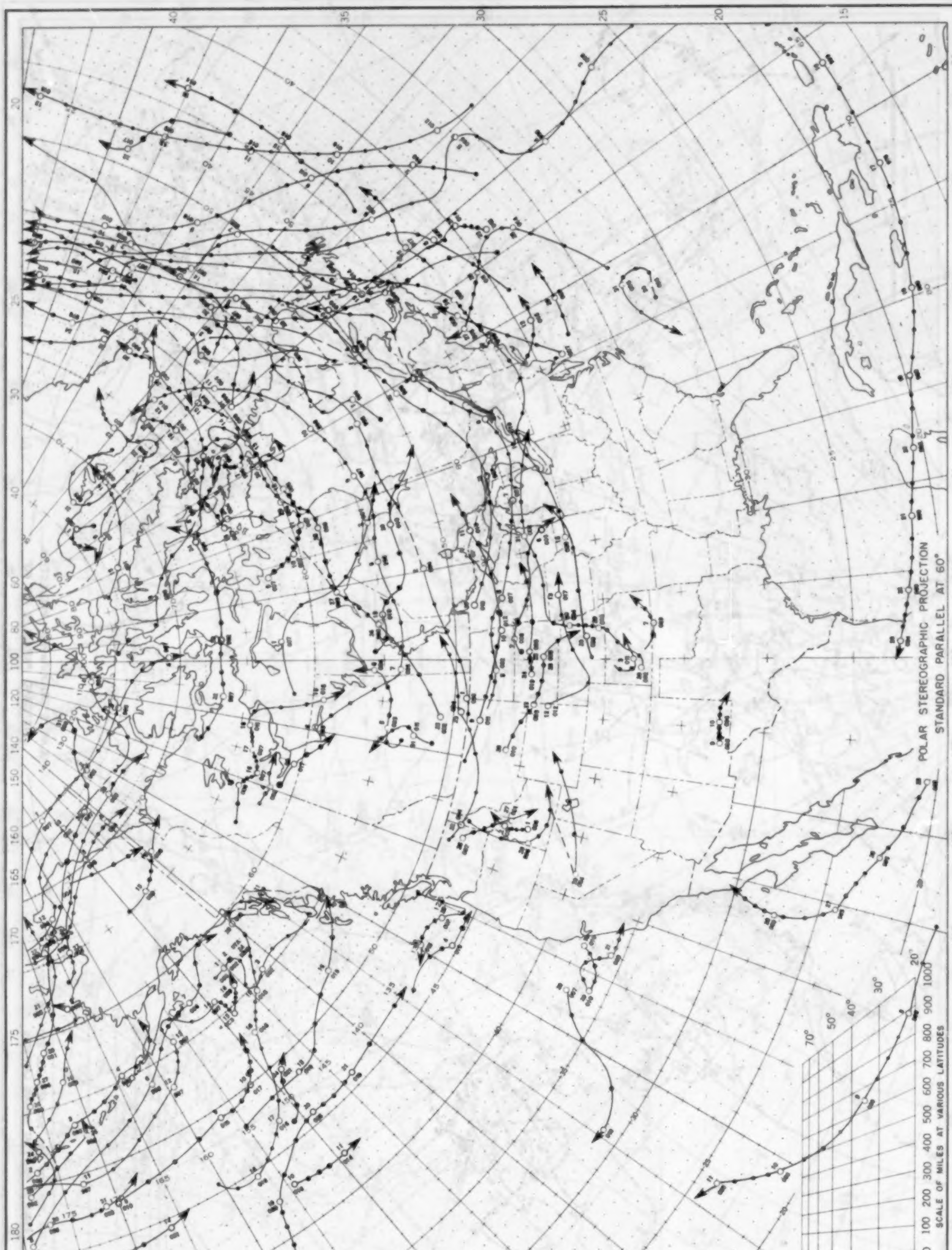
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, August 1951



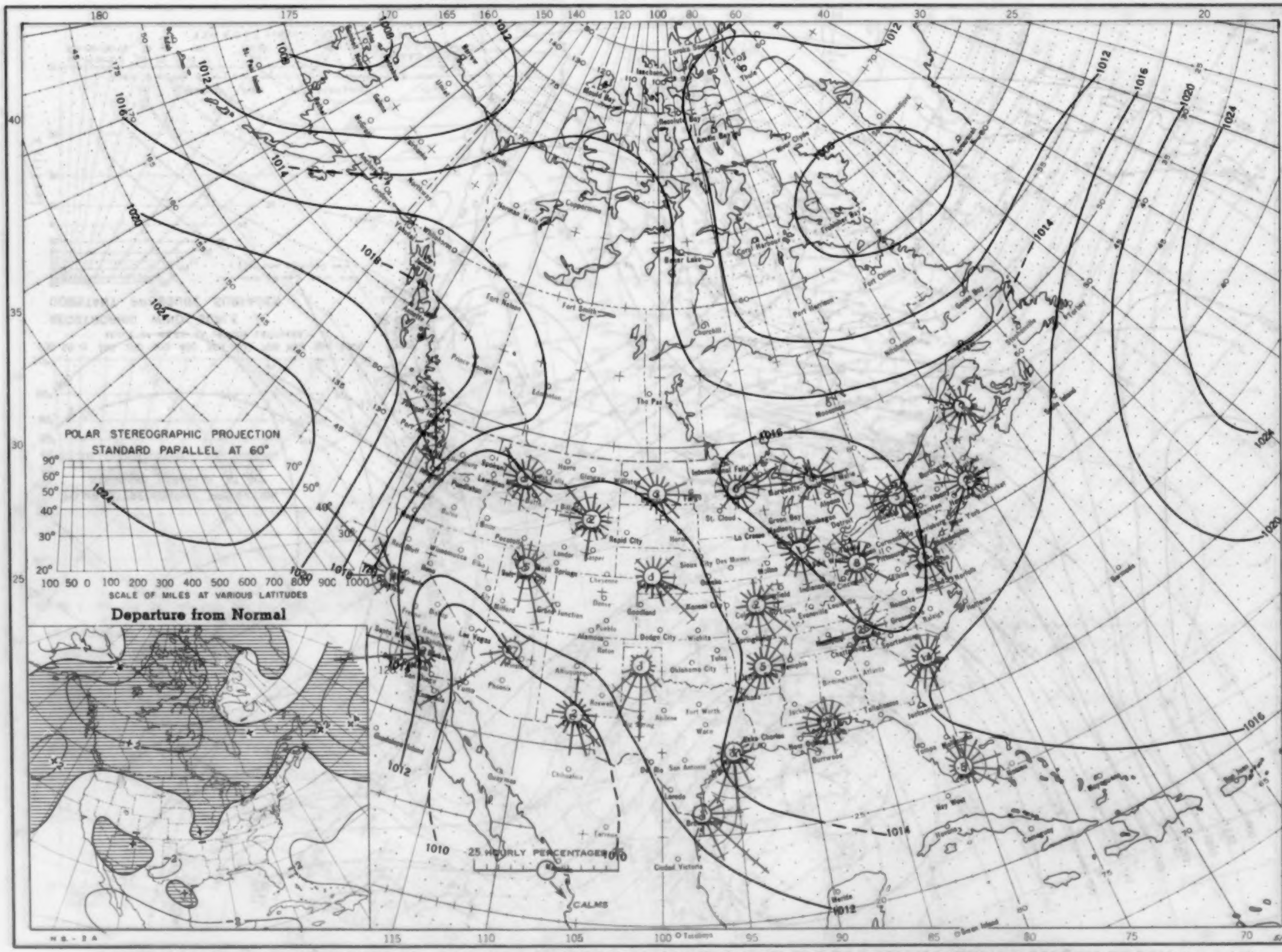
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, August 1951.



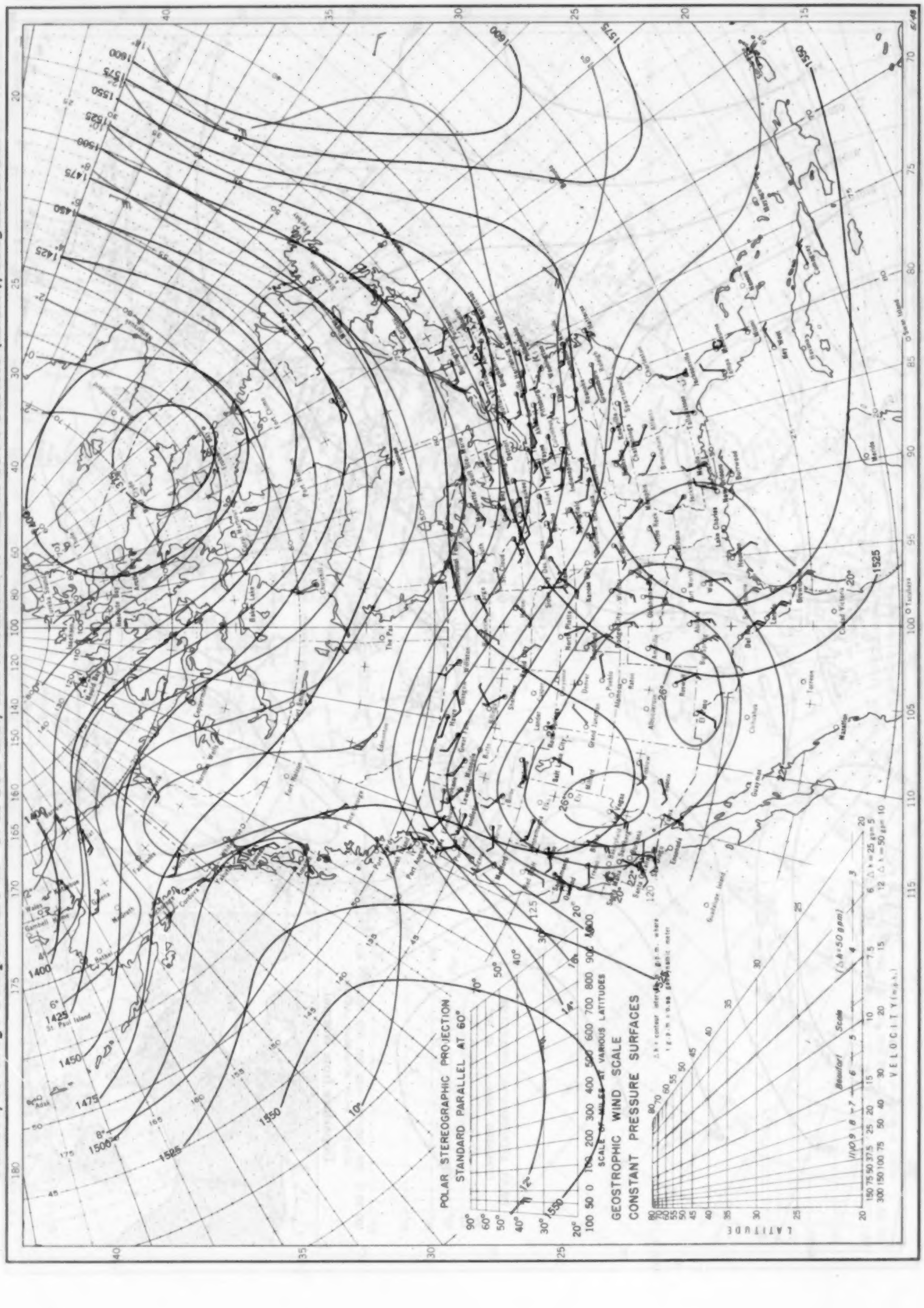
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, August 1951. Inset: Departure of Average Pressure (mb.) from Normal, August 1951.



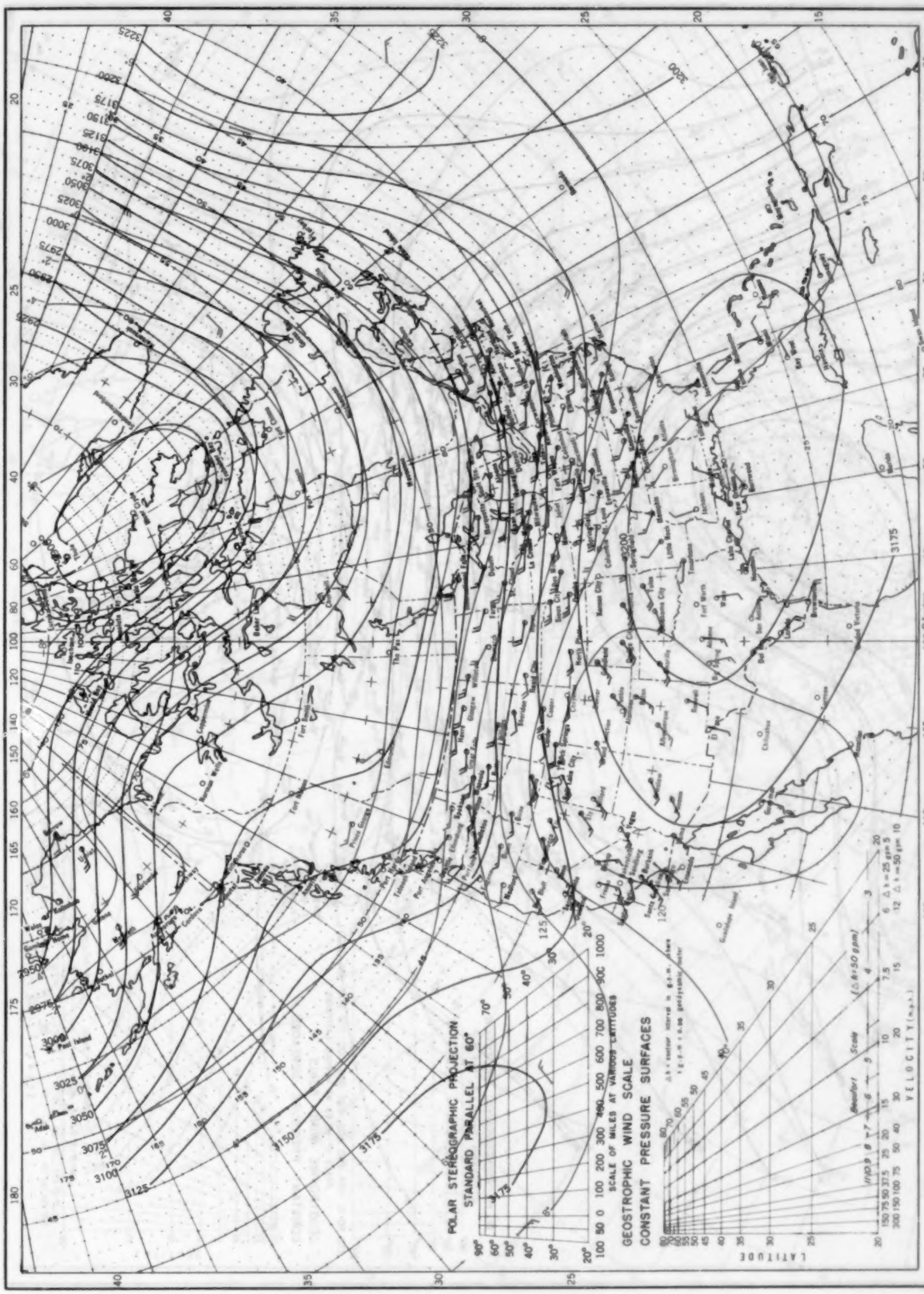
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid from map readings for 20 years of the Historical Weather Maps, 1899–1939.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), August 1951.



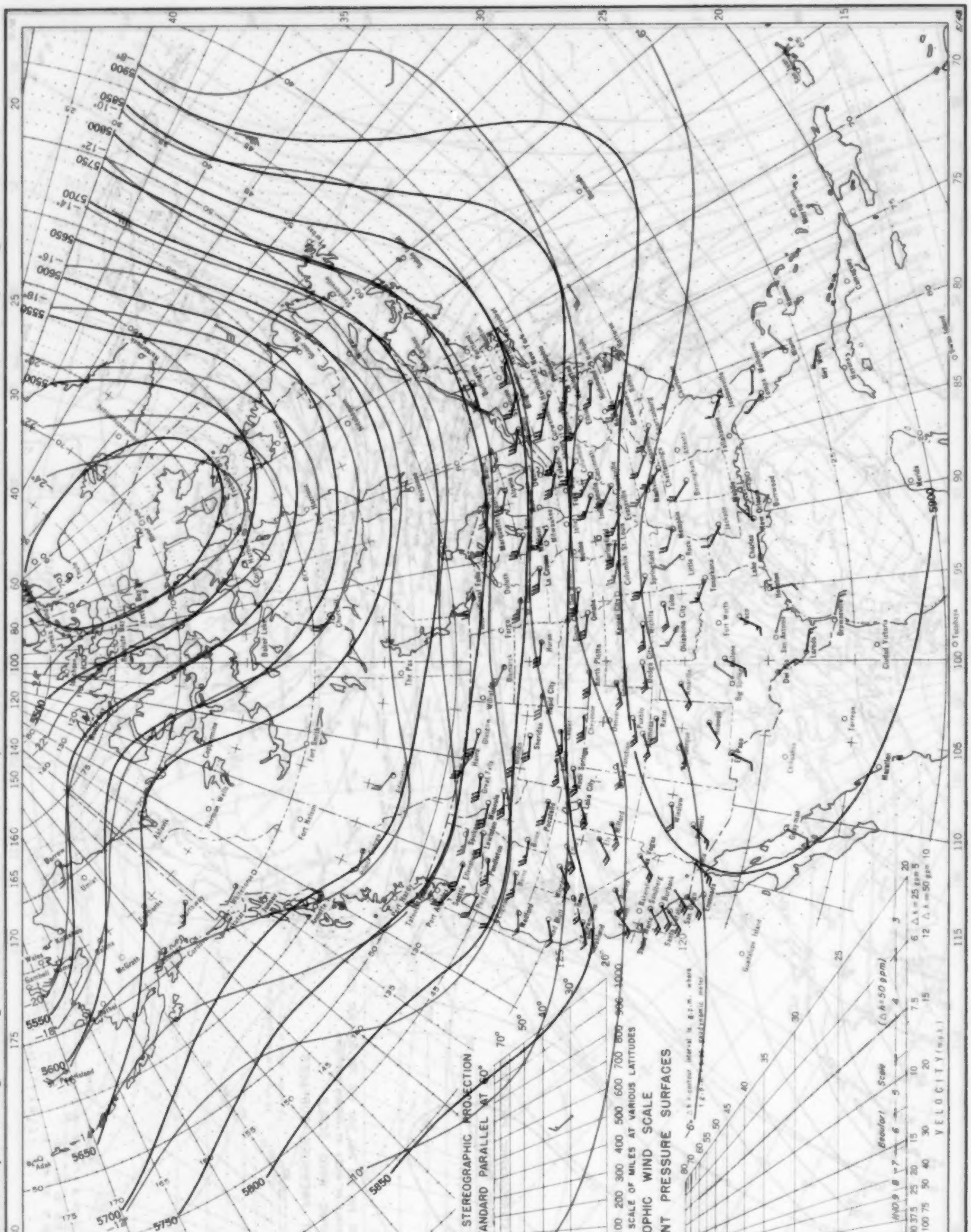
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), August 1951.



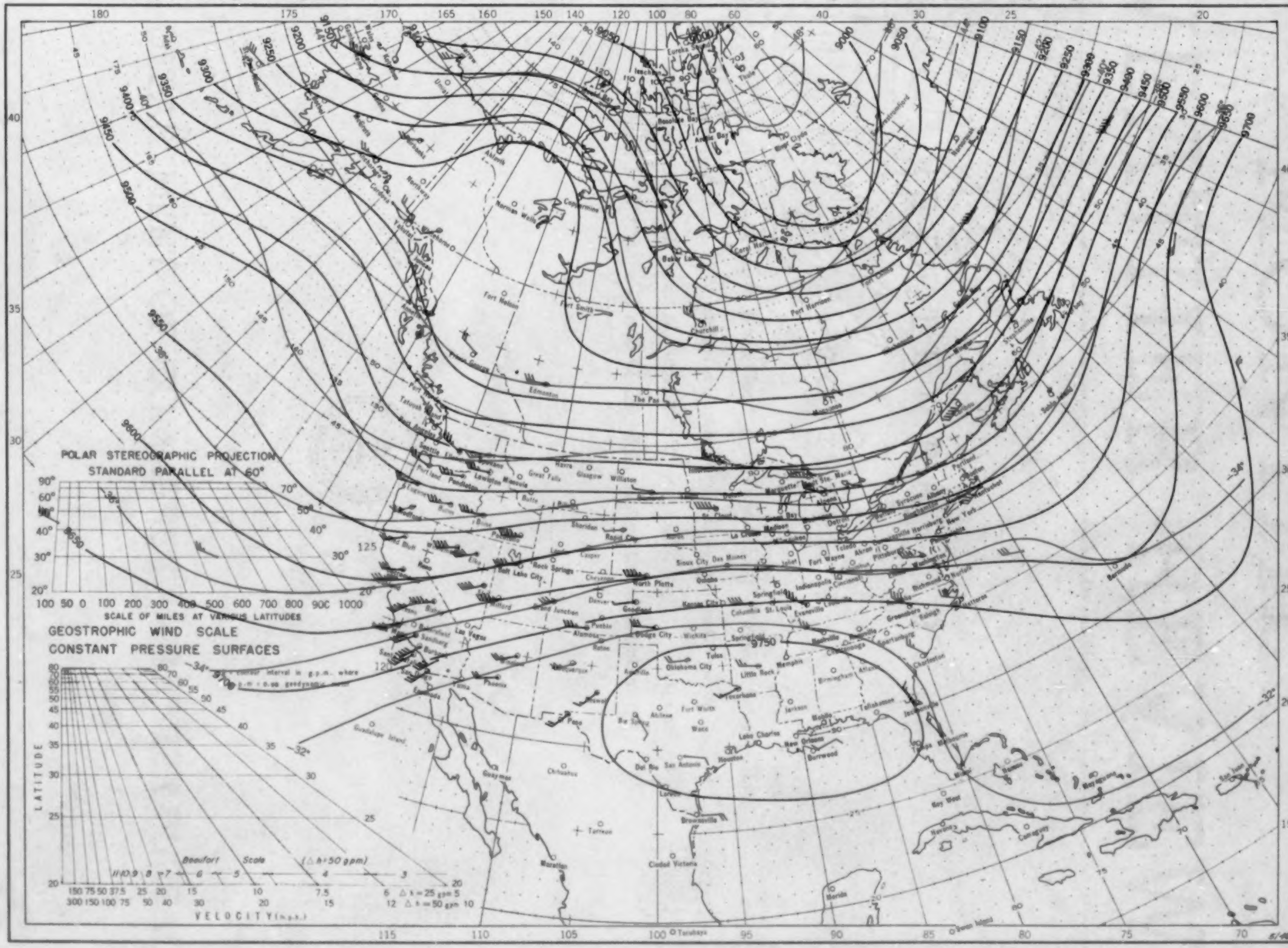
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), August 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), August 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.